Future Generation of Tokomaks with High Magnetic Fields

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Contents

Abstract

In this essay I write a short preview of history tokomaks research and developments and its remarkable achievements. However I will point out an obstacle which made research of fusion energy very difficult because of inability to generate high magnetic field using copper magnets and necessity of constructing big size tokomaks to make fusion energy possible.

However recent development of superconductive materials allowed us to replace copper in magnets, which are able to generate stronger magnetic field for better magnetic confinement. As result of this development ITER (International Thermonuclear Reactor) was designed, which has a promise to draw a pathway to fission energy. Nevertheless ITER still appears too big and expensive.

I will write about the most recent discovery and development of HTSC (High Temperature Superconductive) materials, which can called as a miracle, and which give us a hope to create a new type of magnets with super strong magnetic field and rethink about the tokomak design. Here I will stress on the importance of creating high field magnets for fusion energy. As a proof of availability of these materials I will inform about the USA MAGLAB achievements in developing the most powerful magnetic coils which may revolutionise the fusion energy research.

I will tell about a new MCF device called ARC. Because of its smaller then ITER size, ARC Reactor gives us a promise to solve many problems regarding tokomaks size and cost. By giving the main ARC characteristics, I will show its readability and possibility and emphasise its advanced design with its demountable parts, what makes it resistant to thermal and nuclear damage. To promote the ARC Reactor proposal, a design of even smaller SPARC reactor is considered.

1 Introduction

"Magnetic fusion, as its name implies, requires high magnetic fields"

J P Freidberg

I was inspired by Prof Dennis Whyte's talk which was presented at the Fusion frontiers workshop at York Plasma Institute about "ARC: Affordable Robust, Compact Reactor" with new type high field magnets, and decided to write an extended essay based on his presentation, where actually he and his team claim that fusion energy is feasible right now with the current technologies available.

However being sceptical like every scientist about new ideas, I decided to carry out research on my own on this topic. I explored numerous scientific papers about current status of research and development of high-temperature superconductor materials and magnets generating high magnetic fields. To my surprise the high temperature materials really exists and are commercially available and magnets generating high magnetic field are already completed a few years ago. As a proof of this references of these scientific papers are listed at the end of my essay.

I wrote about previous and current fusion energy projects giving their description and main parameters of tokomaks. I point out the main obstacle which all these projects face. This obstacle is the huge tokomak's size and cost because all these magnetic confinement devices did not satisfy their main requirement which is high magnetic fields. I explain in detail why high magnetic fields are so important in the tokomak design, and if we replace copper magnets by magnets made of high temperature superconducting materials, we will solve the problem.

I wrote about a student proposal of a small and inexpensive tokomak with high field magnets, which will lead to fusion energy with the current technology available.

2 A Long Way to Fusion

Fusion energy research has a long history, promising us an unlimited, inexpensive and clean energy. But because of numerous technological difficulties it was not attainable until now.

2.1 Remarkable results

First tokomak was built in the late 1950-s, and driven by desire to harness inexpensive new source of energy, and supported by generous governments investments the field was growing very rapidly. From 1960 to 1995 dozens tokomaks of different shape, size and designs were built at incredible rate, actually achieving remarkable results. Plasma physics and theoretical and experimental were really popular then, researches were studying this subject quickly and enthusiastically, solving numerous problems. Such tasks and problems as instabilities, diagnostics, heating plasma appeared new to the scientific world but they were solved very quickly.

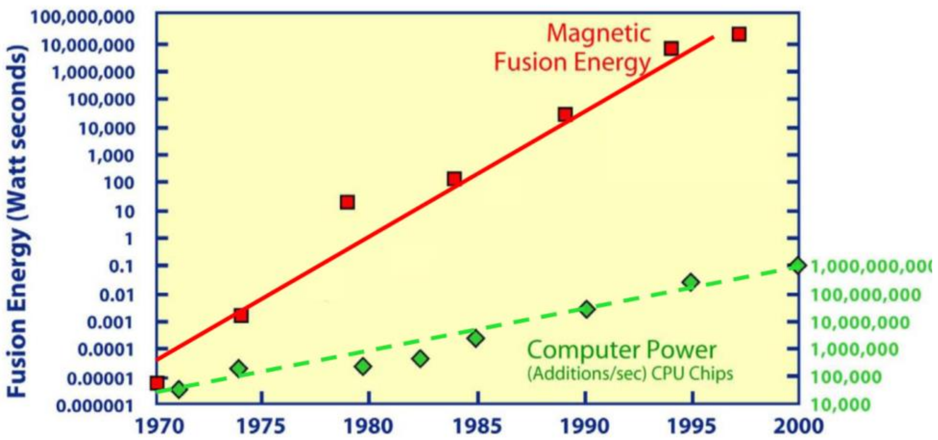


Figure 1 shows the growth rate of Fusion energy and computer power.

If look at the figure 1 how quickly tokomak "power" was growing. It was growing faster than at the exponential rate, faster than such well known computer power "Moore's" law. Scientists were very enthusiastic about tokomaks and hoped that harnessing the fusion energy can be achieved in grasp of their hand.

2.2 Obstacles[2],[3]

However there was one obstacle. As tokomaks magnets were made of copper, the strength of magnetic field which they were able regenerate was limited. As far I know the maximum magnetic field from copper magnets was 3.5 Tesla. Therefore to achieve better performance in order to achieve fusion energy requirements, tokomaks became bigger and bigger requiring for their construction more and more investments and time. One of the recent and the biggest tokomaks which was built in the UK was JET.

It was a big machine with it weight of more than 3,000 tonnes, plasma volume of 100 cubic meters, plasma major radius 2.96 meter, plasma minor radius 1.25 meter, toroidal magnetic field B_0 3.45 Tesla.

Although it achieved remarkable results with fusion power of 10 MW in 1991, it became clear that with copper magnets Magnetically Confinement Fusion is not feasible because of huge tokomaks' size. Some physicists say that "they were stalled".

2.3 A new hope

However, discovery and developments of superconducting materials gave some hopes and expectations. Usage of superconducting materials based on Nb_3 lead to opportunity to build magnets generating high magnetic field B of 5 Tesla and even higher. It became very quickly well-proven technology finding its implications in many fields. The best example of this can be usage of this type of magnets in CERN, the particle accelerator.

Such a success gave a hope of achieving magnetic controlled fusion energy in foreseeable future. The idea was to replace copper in magnets in current tokomaks by superconducting materials, which can generate high B, and it can be essential for achieving high temperature for burning plasma.

These tokomaks can meet fusion reaction criteria and achieve fusion. This is how the idea of a bigger tokomak came. ITER was designed in late 90. It should have following parameters: A major radius equals 6.2 m, minor radius is 2.3 m, toroidal magnetic is 9.2 Tesla; the field fusion energy gain more than five times Q > 5. However, it is still too big and expensive. It's so big and expensive that it takes the whole world to construct it.

Figure 2 shows the real size of a Toroidal Magnetic Field coil completed for ITER.
It is impressive, but it looks too big for the right solution.

3 Current projects

Nevertheless I decided to write here about ITER, the biggest and most ambitious scientific project ever to show the scale and importance of fusion energy research.

3.1 Prehistory

ITER (International Thermonuclear nuclear Experimental Reactor) is an international nuclear fusion and engineering megaproject which will be the world's largest magnetic confinement physicist experiment. It will be with a plasma radius of 6.2 meter and plasma volume of 840 cubic meters. It is an experiment tokomak reactor that is being built next to Caradache facility in the South of France. The ITER project has been designed to produce 500 Megawatts of output power for several seconds while needing 50 Megawatts to operate. The machine aims to demonstrate the principle of producing more energy for the fusion process than it is used to initiate it.

The project is funded and run by seven entities (countries). Constriction of the ITER Tokomak complex was started in 2006 and building cost was US$50 billion. The facility is expected to finish its construction phase in 2019.

3.2 ITER design[11]

Vacuum vessel is the central part of the ITER machine – a double walled steel container in which the plasma is confined by magnetic field. It will weigh 8000 tonnes and have 840 Cubic meters of volume.

Breeding blanket is the key component of the ITER Reactor design. It is the breeder blanket materials for use as a breeder include lithium metatitanate and lithium arthoslicate. It will contain 440 blanket models.

Magnet system is the central coil, which will use superconducting niobium-tin to carry 46 kA and produce a magnetic field up to 13.5 Tesla.

The cryostat is a large 3,800-tonne stainless steel structure surrounding the vacuum vessel and the superconducting magnets, in order to provide a super-cool vacuum environment. Its thickness ranging from 50 to 250 mm will allow it to withstand the atmospheric pressure on the area of a volume of 8,500 cubic meters. In total it will have 54 modules and have volume 16,000 cubic meters.

3.3 Main parameters

ITER will have the following parameters:

- Major radius R =6.2 m
- Minor radius r=2.0 m
- Toroidal field B_0=5.3 Tesla
- Plasma current I_p = 15 MA
- Edge Safety factor q_a = 3.0
- Normalized beta β_N = 1.8
- Average electron density <n_e> = 1*10 20 m^{-3}
- Average temperature <T> = 8 keV
- Average electron temperature <T_e> = 8.8 keV
- Fusion energy gain factor Q = 10 times
- Burning time τ = 400 seconds

4 New magnets [5],[7],[10],[12]

As building high field magnets is a key point for tokomak design, I think it would be relevant here to write here about discovery and developments of high temperature superconductive materials and engineering high field magnets, because this research and development of new superconducting materials lead to rethinking tokomak design and new approach to fusion energy in general.

4.1 The discovery of HTS

High Temperature Super (HTS) conductive are materials that behave as superconductors at unusually high temperature. HTS was discovered by IBM researcher Georg Begnoez and Alex Muller, who were awarded the 1997 Nobel Prize in Physics.

Whereas "ordinary" or metallic superconductive materials have transition temperatures (temperatures below which they are superconductive) below 30 K (-243.2 C) and must be cooled using liquid helium to achieve superconductivity, HTC have been observed with temperatures as high as 138 K (- 135 C) and can been cooled by liquid nitrogen. The first superconductor found with transition temperature bigger than 77 K (nitrogen boiling point) is yttrium barium copper oxide YBaCuO.

4.2 Why HTS materials are so good for magnets[4],[6],[7]

It is important here to describe Magnetic properties of HTC as it is an essential part for engineering high field magnets.

All known high transition temperatures superconductors are Type II superconductors. In contrast to Type I superconductors, which expel all magnetic field due to Meisser Effect, Type II super conductors allow magnetic fields to penetrate into their interior in quantized units of flux, creating "holes" or "tubes" of normal magnetic regions in the superconductive bulk called vortices. Consequently, high temperature superconductors can sustain much higher magnetic fields. This property enables us to engineer high field magnets.

The discovery of new superconducting materials is still continuing. In 2015, hydrogen sulphite (H_2S) under externally high pressure (around 150 Giga Pascale) was found undergo superconductivity transition.

"High-temperature" has two definitions in the context of superconductivity: firstly, above the temperature of 30 K, secondly, having a transition temperature that is larger fraction of Fermi temperature than for conventional superconductors.

The development of superconductive materials was not easy, numerous scientific laboratories were involved in research during two decades after the discovery of HTS more than 100,000 papers on the subject were published. However, no widely accepted theory explains the physics of superconductivity yet.

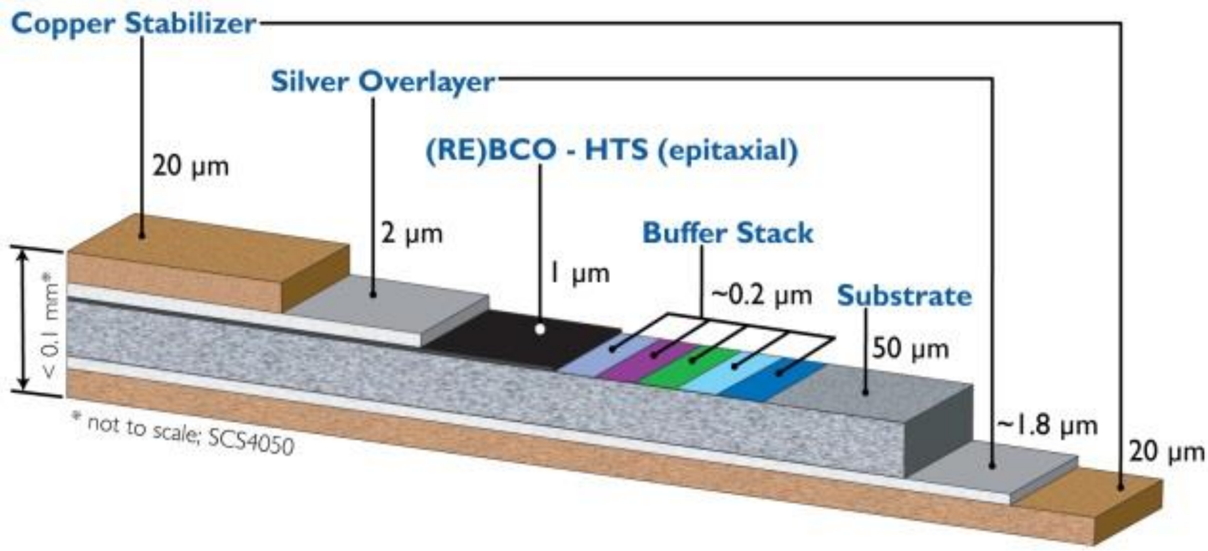


Figure 3 shows a schematic design of REBCO wires in the shape of tapes.

Nowadays a superconductive wire is being manufactured using REBCO (Rare Earth Barium Cu-Oxide) in shape of a tape coated by others compounds such as copper, silver, hastelloy and others. REBCO (Rare Earth Barium Cu-Oxide) remains superconducting at very high magnetic field, and above liquid helium temperature. This material has unique properties. It is strong in tension to steel, flexible, radiations resisted, allows simpler coils design doesn't require reacting after winding.

The first tapes were produced about 10 years ago of length of one meter only. Nowadays the length of the tape exceeds 1000 meters and commercially available at affordable price. One of the leading manufacturer of REBCO tapes is SuperPower Ltd.

4.3 Magnets with super-high magnetic field

The developments of REBCO or YBCO tapes were successfully implemented in engineering magnets. One of the company which specialises in engendering of super strong fields magnet is Mag Lab and its achievements are really impressive. I think it would relevant to tell here about this company, because making magnets generating super strong magnetic field is the key point for design of new generations of Magnetic Confinement Devices. Because the stronger magnetic field the smaller and cheaper tokomaks will be.

National High Magnetic Field Laboratory is located at Florida State University, its history comes from 1980. This company is specialises in development and engineering high magnetic field magnets, which find application in numerous arrears: science- Accelerators, Medicine MRI machine, industry. Over the years the lab has continued to break record after record for resistive magnets (27 Tesla, 30 Tesla, 35 Tesla, 36.2 Tesla), hybrid magnets with 45 Tesla. Whereas the world magnet record was 22.3 Tesla until 2007, the Mag lab using discovery of YBCO, Type II superconductor, a revolutionary new technology of making wire in form of tapes, completed a magnet being able to generate 26.8 Tesla.

In 2009 the lab started working on even a more ambitious project, engineering a magnet with 32 Tesla. They decided to use "YBCO", a superconducting ceramic composed of yttrium barium, copper and oxygen. This magnet combines High Temperature and Low Temperature Superconductors. So the magnet has 2 coils made from "YBCO", 3 coils from Niobium-Tin, and 2 coils from Niobium-Titanium. The project was completed in 2015 demonstrating magnetic field of 32.2 Tesla. They results were published in numerous scientific papers. The researchers are very optimistic about the future: "In principle "YBCO" is capable of producing the high field superconducting magnets ever possible. It's even possible that it could be one day produce magnetic field as high as 50 Tesla", said one of the leading Mag lab scientists.

5 The ARC Reactor

The full description of ARC reactor can found in the original paper "ARC: A compact, high-field fusion nuclear facility and demonstration power plant with demountable parts" published in ELSEVIER in August 2015. ARC stands for as the Affordable, Robust, Compact reactor. It is a conceptual design study aimed at reducing the size, cost and complexity as a fusion nuclear science facility and demonstration fusion power plant.

5.1 Description of ARC Reactor

ARC is a 200 – 250 MW tokomak with a major radius 3.3 m and a minor radius of 1.1 m, plasma volume 141 cubic meters, with an on-axis magnetic field of 9.2 Tesla. The design predicts a plasma fusion gain factor Q_p =13.6.

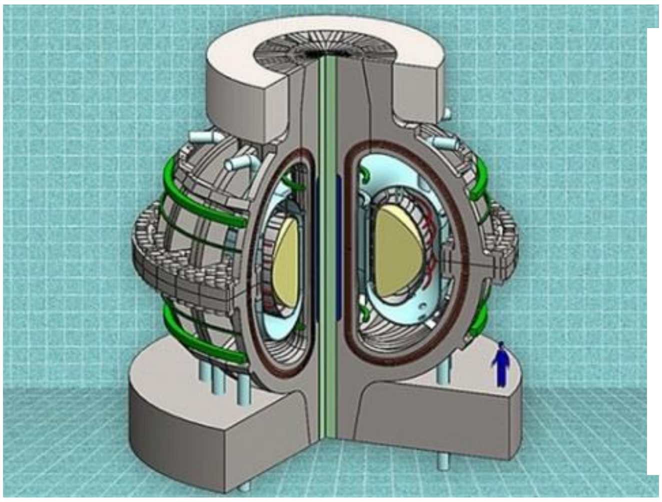


Figure 4 shows schematic ARC reactor design.

The Reactor which is fully non-inductive. It will use magnets with type II of superconducting materials and have a "liquid" blanket and consist of demountable modules.

5.1 Design method[1]

In order to determine a starting point for the ARC parameters, a 0-D design was performed. The design was iterated several times using such codes as ACOME, MNCP, COMSOL. Data from previous tokomaks as JET, Alcor C mode were used for performing scaling.

A fundamental equation for any magnetic reactor design is the scaling

$$\frac{P_f}{V_p} \propto 8 < p >^2 \propto \beta_l^{\,2}\ B_0^{\,4}$$

For volumetric fusion power density $\frac{P_f}{V_p}$, where $< \mathrm{p} >$ is the volume averaged plasma pressure in MPa. This gives two strategies to increase parameter $\beta_T = \frac{2\mu<p>}{B_0{}^2}$ or increase magnetic field. The ARC design is chosen to increase magnetic field B_0. The desire to increase elongation as much as possible is well understood by combining equation for scaling and equation for safety factor, which gives $\frac{P_f}{V_p} \propto \left(\frac{\beta_N \epsilon (1+k^2}{4q_a}\right)^2 B_0{}^4$

Variables in brackets will be constant in our case. From the equation we clearly see that efficiency of the device depends on $B_0{}^4$, what proves the importance of high magnetic field for MSF devices.

5.2 Main ARC parameters[1]

So using the scaling the main ARC parameters were calculated.

- Fusion power P_f = 525 MW
- Total thermal power P_{hot} = 708 MW
- Total electric power P_e = 283 MW
- Net electric power P_{net} = 190 MW
- Major radius R_0 = 3.3 m
- Plasma semi-minor radius a = 1.13 m
- Plasma elongation k = 1.84
- Plasma volume V_P = 141 m^3
- Toroidal magnetic field B_0 = 9.2 Tesla
- Peak on-coil mag. Field B_{max}= 23 Tesla
- Plasma current I_P = 7.8 MA
- Bootstrap fraction β_{BS} = 0.63
- Average temperature <T> = 14 keV
- On-axis temperature T_0 = 27 keV
- On-axis density n_0 = 1.8 x 10 20 m^{-3}
- Toroidal beta β_T = 1.9%
- Normalised beta β_N = 2.59 %
- Safety factor at r/a = 0.95 q_{95} = 7.2
- Edge safety factor q_a = 4.7
- Minimum safety factor q_{min} = 3.5
- Energy confinement time τ_E = 0.64 sec
- Confinement factor G_{89} = 0.14

For calculating temperature and density profiles it was required to input into the ACCORME current equilibrium code with safety q_a from 6 to 7.2. From this the ARC operating point plasma has volume average temperature T_e ~ 13.9 keV and volume density n_{20}~ 1.3, the on-axis temperature T_e ~ 27 keV, and density
n_{20} ~ 1.75 and beta β_N = 2.59.

5.3 Core physics[1]

Due to the high magnetic field and compact nature of ARC, it was chosen to explore I-mode regime, which has produced excellent absolute and scaled performance in the field. I-mode is characterised by L-mode-like particle confinement and Hi-mode-like energy confinement, making it an attractive regime for reactor because it may allow for easier control of density critical features.

However, I-mode has not been studied well yet. Therefore, the ARC design will simply use the scaled density, the temperature from Alcor I-mode on C-mode.
Also ARC tokomak will explore an attractive approach to current drive in burning plasmas. Lower hybrid waves, launched from the high field side of the tokomak, are used to nonconductively drive plasma current. High field side launch is shown modelling to increase the current drive, which crucial to maximising control of the radial current profile.

5.4 Magnets

A central aspect of the ARC conceptual design is exploring possible fusion reactor/ FNSF scenarios at the much higher magnetic field afforded by REBCO superconductors. It is imperative to explore these new magnet designs to understand trade-offs and limitations.

The magnet system is divided into four groups: Toroidal Field (TF) coils, Poloidal Field (PF) coils; The Central Solenoid (CS), The Auxiliary (AUX) coils.

The first two groups (TF and PF) are steady state superconducting magnets that provide magnetic field for stability, shaping and start-up. TF coils will support a magnetic field of 9.2 Tesla on axis with a peak of 23 Tesla on coils. The CS will be used primary for inductive start-up of the plasma current. The auxiliary (AUX) coils are copper magnets that carry relatively small currents for real-time shape adjustments. TF magnets will be made of REBCO superconducting tapes.

As figure 3 shows a schematic view of the cross section of commercially available REBCO type conductor by Superpower Inc., REBCO is a high temperature superconductor, meaning it can operate at temperature up to 80 K, which is much higher than 4.2 K necessary for Nb_3Sn. However the ARC tokomak will need to operate at 20 K.

The TF coil system is composed demountable TF coils with stainless steel. Each TF coil will require 120 CICC cables and total number of superconducting tapes turns is 106 tapes/cable x 120 cables/ coil x 18 coils = 230,000. The total required length is 5730 km. However the length of the individual CICC cable is only 17 m. Compared with continues coil winding such as ITER, ARC requires relatively small length.

5.3 Demountable parts

The biggest concern of tokomak design is neutron damage. It has been calculated that some tokomak parts can damaged by neutron radiation just 2 or 3 month of a continuing operation and replacement or repairing of the part will be needed. However the most of tokomaks are made as single units and replacement of their parts is impossible and repairing is very difficult and expensive. The most vulnerable part of tokomak will be its blanket. So lifetime of the future tokomaks will be only a few months, which is not enough.

To solve this problem the ARC Reactor is designed as a set of demountable modules. For example when one of part of tokomak is damaged by neutron radiation, it can be easily removed and replaced by new one, and the tokomak as a device can work for long.

The most challenging for making a tokomak as a set of modules is a design of compounds electromagnetic coils which will contain two parts – the fixed low leg and demountable upper leg. This design will allow to remove upper legs of coils by a single vertical lift.
Two parts of the coil will be connected by electrical joints. Making the joints is the most challenging and delicate task.

The electrical joints between the two legs of the TF coils were chosen to be “comb-style”. This design is robust to slippage in the direction of the tapes, as a slight movement of tapes does not significantly change the joint electrical resistance. Each TF coil requires 240 sets of combs in series. Each set of comb is insulated with Kapton and S2 glass. The design of joints insulation schemes are under development but not understood well.

5.6 The ARC Reactor Cost

The main purpose for minimizing the size of ARC is to reduce the cost of building reactor. While it is difficult to calculate an exact full cost of ARC reactor, we used some approximation methods. First, we can estimate the total cost by a method based on volume and materials prices obtained from a commodity price list.

From the table we can see prices of main materials which will be used in tokomak.

- Beryllium $257/kg
- Inconel $56/kg
- Tungsten $29/kg
- Stainless steel $9.6/kg
- Copper $8.3/kg
- REBCO tape $18 – 36 /m
- FLiBe $154/kg
- Ti H_2 $26.4/kg

Because the ARC reactor with its radius of 3.2 m is similar to size of tokomaks (JET, TFR), which have already been built, it would be appropriate to use the same scaling system. In order to access the bulk material cost of the ARC reactor it was decided on three subsystems: the replaceable vacuum vessel, the blanket, the magnets and their structure.

Materials prices were obtained from commodity price lists, although prices of the REBCO tapes, and FLiBe were taken from manufactures. To calculate a volume of materials MNCP model was used. Then knowing volume and price the cost was calculated. The most expensive components of the reactor are:

- The blanket $73 M
- Magnet structure steel $42 M
- REBCO types $100 – 200 M
- The total cost of material $330 and $430 M.

In order to provide a better cost estimation than just a simple fabrication costing, a rough scaling was employed. Using this methods we calculated the total cost per weight unit. In this method, the total projected costs of four designs (FIRE, BPX, PCASSTS and ARIES-RS) were divided by the weight of the device. These four costs were approximately the same regardless the machine specifics. From this point, we can assume that the same fabrication prices will apply for the ARC reactor and will be $1.06 M per tonne of the device. So, the estimated total fabrication cost of the ARC reactor will be $1.06 x 7190 tonne = $5,500 M = $5.5 B.

From the figures calculated above it can be summarized that the total materials cost is less than $0.5 B, while the total fabrication cost is more $5.5 B. From this we can clearly see that total materials cost is a tiny fraction of the total fabrication cost. Actually when we make a decision which tokomak to build materials cost can be ignored. We can clearly see that the ARC reactor is already much cheaper than ITER. Furthermore, the cost, especially fabrication cost, of ARC will be significantly reduced in the future, if multiple machines are built.

6 SPARC (Soonest/Smallest Private-Funded Affordable Robust Compact) Reactor[14]

I was interested to read a presentation performed by MIT students about a new approach to Fission Energy and their schematic design of a small tokomak. It was called as "SPARC (Soonest/Smallest Private-Funded Affordable Robust Compact), a small high field torus for changing climates" "Thoughts on new technology, private funding, and modern innovation techniques to accelerate fusion energy" written in their presentation by B. Mumgaard, Z. Hartwig, B. Sorbom, D. Brunner.

We can agree or disagree about their opinion about some controversial issues, but I find their approach to the problem intriguing and decided it would be suitable to write here about their ideas. Also, I decided to write about this presentation because it seconds Prof Dennis Whyte papers "ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets" and proposal which were represented in "Frontiers of Fusion" workshop.

6.1 A smart solution

Their presentation is not only fusion physics but about history, strategy in scientific research and development, how to find funding, difference between public and private funding, how to complete a project on a budget and in time – about all these things without which science would not be possible.

They compare Research in Fusion Energy with other fields, particularly with space exploration. They concern about big "mammoth", multibillions projects, arguing that some of these huge projects overrun the budget, fell behind schedule and jeopardise small and small, but promising projects. They encourage to find inexpensive and clever solutions to solve problem and push "R&D" ("Research and Development") forward.

They give such an example of an inexpensive and successful project as "Pathfinder", the American spacecraft, which successfully landed on Mars and performed its task. This mission paved the way for a robust Mars program, which was really impressive.

The authors of the presentation promise that a small tokomak with High temperature Superconducting materials can be that "Pathfinder" and will pave the way for robust Fusion Energy research and development. It can encourage the scientific community and private business to build a new generation of tokomaks with a new type of superconducting magnets.

6.2 Conceptual design

They draw a schematic design of that small tokomak and called SPARC (Small Private Affordable Robust Compact). According the proposed Spark design, the device will be in 10 times smaller in volume than the ARC Reactor and have a major radius about 1.5 m. It will produce net energy about from 50 to 200 MW and have fusion energy gain factor Q around from 2 and 5. The tokomak will run in short plasma pulses with a length of 10 seconds.

A new 3D parametric tokomak builder for MNCP (Monte Carlo Particle Code) was created, which predicted that having a thin blanket would be enough for protection from neutron radiation and heat. As the device is small, it can't be afforded to employ a blanket of width of 1 m. As HTS magnets have much higher operating temperature, the magnets don't need be protected from the vessel heat and will be able to survive after thousands plasma shots. So it was decided to have a blanket with width of 15 cm only.

To make device cheaper, it was decided to build a tokomak as a whole unit without demountable parts. If we use the similar scaling analysis for estimating cost, which was used for the ARC Reactor, we can get figure about $0.5 B for SPARC cost.

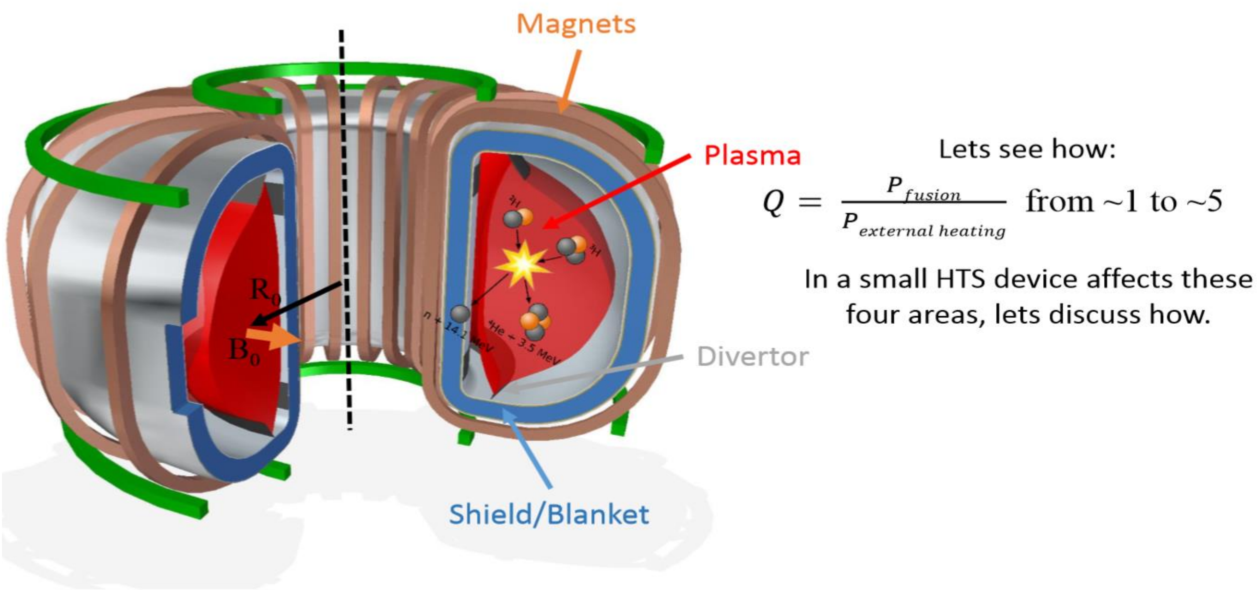
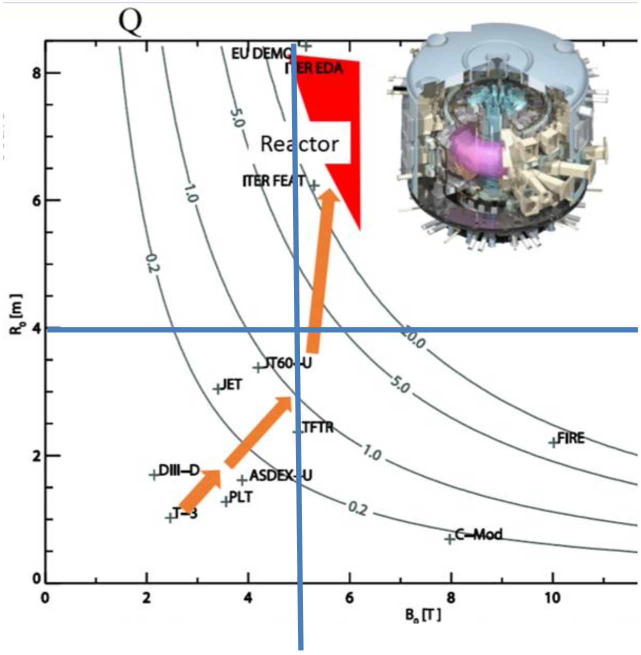


Figure 5 shows schematic SPARC tokomak design.

6.3 R-B plan

To show the importance of the strength of magnetic field and opportunities which HTS can give to Magnetic Confinement Fusion the authors draw such a called R-B plan.



5 Tesla

On figure 6 x-axis represents magnetic field, and y-axis show the size or major radius of the tokomaks, the curves lines show fusion energy gain factor Q

This formula represents energy gain factor.

$$Q \equiv \frac{P_{fus}}{P_{heat}} = \frac{1}{\eta_{heat} \cdot f_{recirc} \cdot \eta_{elec} \cdot (1 - f_{ch})}$$

It can be approximately divide the plane on four areas:

N 1, where B<5 Tesla, R<4 meters, Q <1
N 2, where B <5 Tesla, R>4 meters, Q>1
N 3, where B>5 Tesla, R< 4meters, Q>1
N 4, where B> 5 Tesla, R> 4 meters, Probably Q >10 or even higher

The most present tokomaks were built with parameters from first area N1 with major radius less than 4 meters and toroidal magnetic field B less than 5 Tesla, as result they have fusion energy gain Q less than 1, which means they consume more electricity rather than produce.

As long the magnets generating magnetic field stronger than 5 Tesla were not available until now, the only option to increase fusion energy gain factor was moving up along y-axis, increasing the major tokomak radius. What actually have been done for ITER design.
But ITER size and cost are scarring. This option does not lead to easy "R&D" in Fusion Energy.

However, recent research and development of magnets using REBCO tapes generating super strong magnetic field changed the game. This means that area 3) where R<4 meter and B>5 Tesla is available from now. It makes possible to build small tokomaks with high fusion energy gain factor Q >1, producing net power.

Area N 4 will be available as well – fusion reactors with big major radios R>4 and B>5, will have externally high fusion energy gain factor Q>100, being able to generate hundreds of GW.

6.4 Fusion Energy Roadmap

The authors of the presentation suggest a possible roadmap to fusion, which can be completed, as they claim, in 20 years.

The very first step is to build SPARK, the smallest and simplest tokomak, but with model HTS coils and conductors. SPARK will give net energy gain and demonstrate that high-field HTS magnets can employed in MCF devices. It can be done by 2021.

Next step is to design a reactor with jointed coils and a liquid blanket and shield, with an advanced diverter, steady state current drive and long-pulse plasma physics. It can be done by 2026.

The final step would be building a commercial reactor giving net electricity to the grid. This reactor will have tritium breeding, neutron resistant materials, long lifetime components. This final goal can be achieved as soon as by 2036, or in 20 years from now.

7 Comments and personal opinions

I am very excited about the idea of a smaller and cheaper tokomaks. However I realise physics of Magnetic Confinement devices may so comprehensive, where every single detail should be taken into account, that I became concerned the idea of small tokomak with the high magnetic field is feasible.

So being concerned that I missed something essential in tokomak physics, I decided to ask experts in the field – lectures, professors, just friends who have been working for Fusion Energy for many years, their opinion about ARC Reactor, about the feasibility of the project.

To my surprise, all of them confirmed that physics described in ARC Reactor by Prof Dennis Whyte makes sense, and by generating a stronger magnetic field will make possible to decrease tokomak size. They said that we did not have such experiments yet, but extrapolating and analysing previous results, it looks like Prof Whyte say right figures.

However some people whom I asked were concerned about strategy of developing Fusion Energy. If even ARC Reactor design is good and construction is a feasible, what should we do with ITER project, which is already underway? Some physicists answer that high field magnets are not everything. They explained that the ITER project gives us opportunity for studying many things as theory, plasma physics, materials, developing diagnostics tools which essential for successful fusion energy research and industry.

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