10th Festival de Theorie, July 1-26, 2019, Aix-en Provence

The large tokamak JT-60: A history of the fight to achieve the Japanese fusion research mission

Mitsuru Kikuchi
Former director of JT-60 and ex-supreme researcher of JAEA
ILE, Osaka University, SWIP

References

1. M. Kikuchi, the European physical journal H 43, 551(2018)
2. M. Kikuchi, M. Azumi, Reviews of Modern Physics 84,1807(2012)
3. M. Kikuchi, Frontier in Fusion Research – Physics and Fusion (2011)
4. M. Kikuchi, M. Azumi, Frontier in Fusion Research II – Introduction to Modern Tokamak Phys

This talk is dedicated to former executive director of JAERI, Hiroshi Kishimoto

Contents

1. Prior to JT-60: Start of Japanese fusion program

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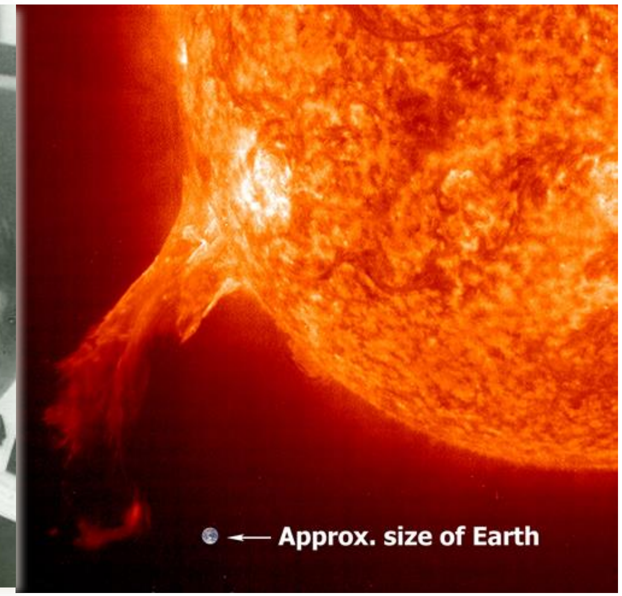
Homi Bhabha(1955) in1st Geneva Conf.

Fusion: Bring the Sun on Earth



1st Geneva Conference (1955) H. Bhabha(president):

I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades"

Atomic Energy Commission of Japan (AEC-J) was formed in 1956.

1955 1st Geneva conf.

1. Prior to JT-60: Start of Japanese fusion program

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1958 2nd Geneva conf.

2nd Geneva Conference (Sept. 1-13, 1958)
H. Bhabha (session chair): Possibility of Controlled Fusion
Speakers: Hannes Alfven, Peter Thonemann, Lev Artsimovich, Edward Teller, Ludwig Biermann

Edward Teller: Economic exploitation of controlled thermonuclear reactions may not turn out to be possible before the end of the 20th century. Nevertheless, the ultimate goals toward which we are working are apt to be highly rewarding.

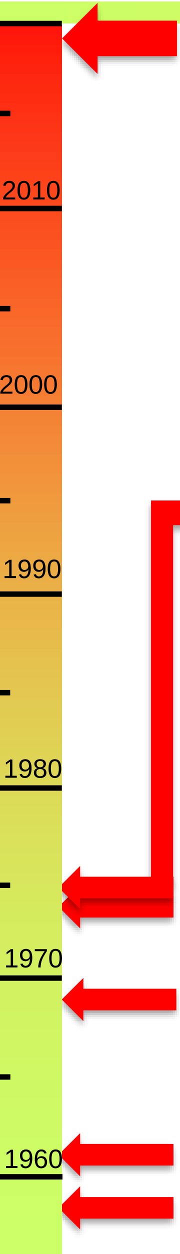
Hideki Yukawa(1958) in 2nd Geneva Conf.

Japanese 1st Nobel Laureate Hideki Yukawa jointed 2nd Geneva conference to watch the controlled fusion session talks and thought about how to start Japanese Fusion Program.

AEC-J formed roundtable committee (Yukawa chair) on fusion reaction February 1958 reporting importance of start fusion research in Japan.

AEC-J Special committee on fusion (April 1958-June1959, Yukawa chair) recommended both basic and project research (A+B).

1. Prior to JT-60: Start of Japanese fusion program



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Driver for Fusion Research:
-1973: 1^{st} Oil shock
-1979: 2^{nd} Oil shock

Fusion Roundtable
Chair: Goro Inoue(AEC-J deputy chair)
Member:
Toshio Doko(Toshiba), K. Komai(Hitachi)
K. Kikawada(TEPCO),Y. Ashihara(KEPCO)
Otosaburo Kato(Electrical Industry Federation)
Koji Fushimi(Science Council)
Takashi Mukaibo(U. Tokyo) et al.

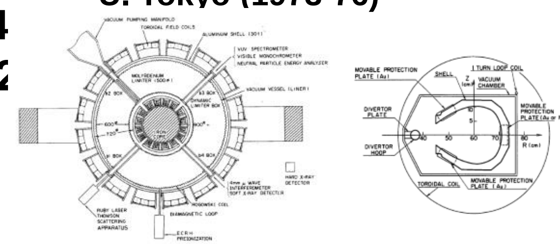
1975: Fusion Roundtable under AEC-J
(Goro Inoue, Chair) [2^{nd} phase fusion program]
JT-60 (tokamak with equivalent break-even)
Non-circular tokamak (later by US-J Doublet-III)
-Fukuda-Carter agreement(1978)-
Fusion technology (SCM, Tritium, Blanket, etc.)
1974: IAEA conf. plasma phys. & Cont. Fus.(Tokyo)
1968: Special committee on fusion under AEC-J
(S. Kikuchi, chair) [1^{st} phase fusion program]
JFT-2a (DIVA, poloidal divertor, constructed 1974
JFT-2(adopt "tokamak" in 1970, constructed 1972
JFT-1 (multi-pole, 1968-69)
1961: IPP-Nagoya established (K. Fushimi, director)
1958: Special committee on fusion under AEC-J
(H. Yukawa chair) A+B

T. Ohkawa S. Yoshikawa

Multipole

Spherator

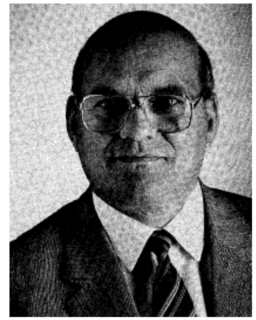
S. Yoshikawa played key role in promotion of JT-60 construction
U. Tokyo (1973-76)



JFT-2 and JFT-2a(DIVA)

2. JT-60 is one of three large tokamaks

Stix, Furth, Teller, Strauss, Rosenbluth, Gottlieb 1967



P.H. Rebut

B_{max}=7T
W_{mag}=1.5GJ

H. Kishimoto

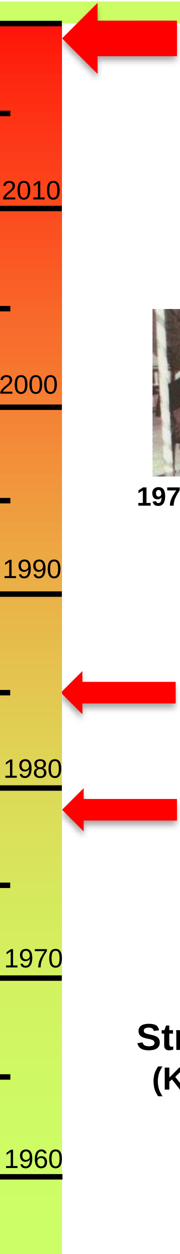
B_{max}=10T
W_{mag}=2.8GJ

Dec. 1982 first plasma

Sept. 1984 first plasma

April 1985 first plasma

2. JT-60 device construction 1978-1985



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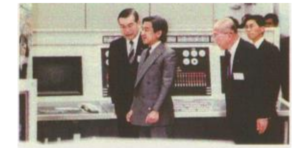
First plasma

Groundbreaking

1982. 05 Prime minister Mr. Z. Suzuki

1982. 09 Prime minister Ms M. Thatcher

1984.11 Prime minister Mr Y. Nakasone



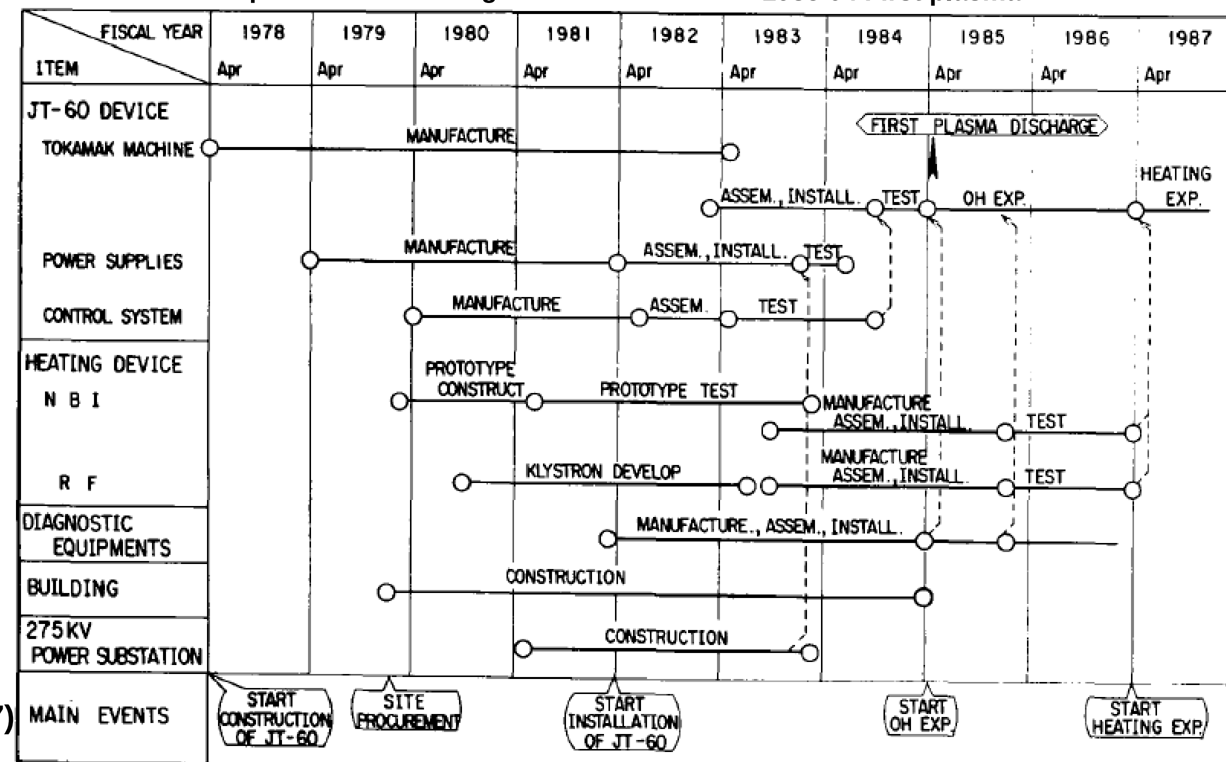
1986.09 Prince Akihito

1979.12 Groundbreaking

1983.06 JT-60 Experimental Building

1985.04 First plasma

Strong supporter Mr T. Doko (KEIDANREN) Visited PPPL 1980 Visited Naka 1985.03



H. Kishimoto, FED, 5,9(1987)

2. JT-60 device construction 1978-1985

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First plasma

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Groundbreaking

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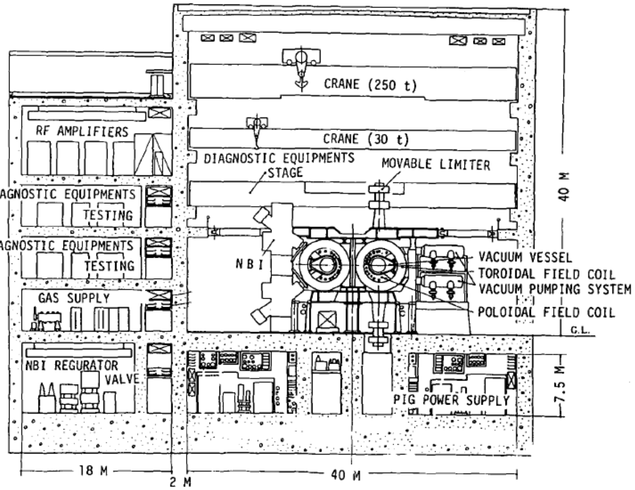
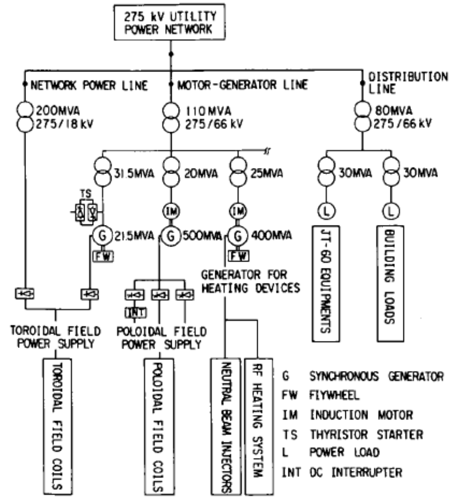
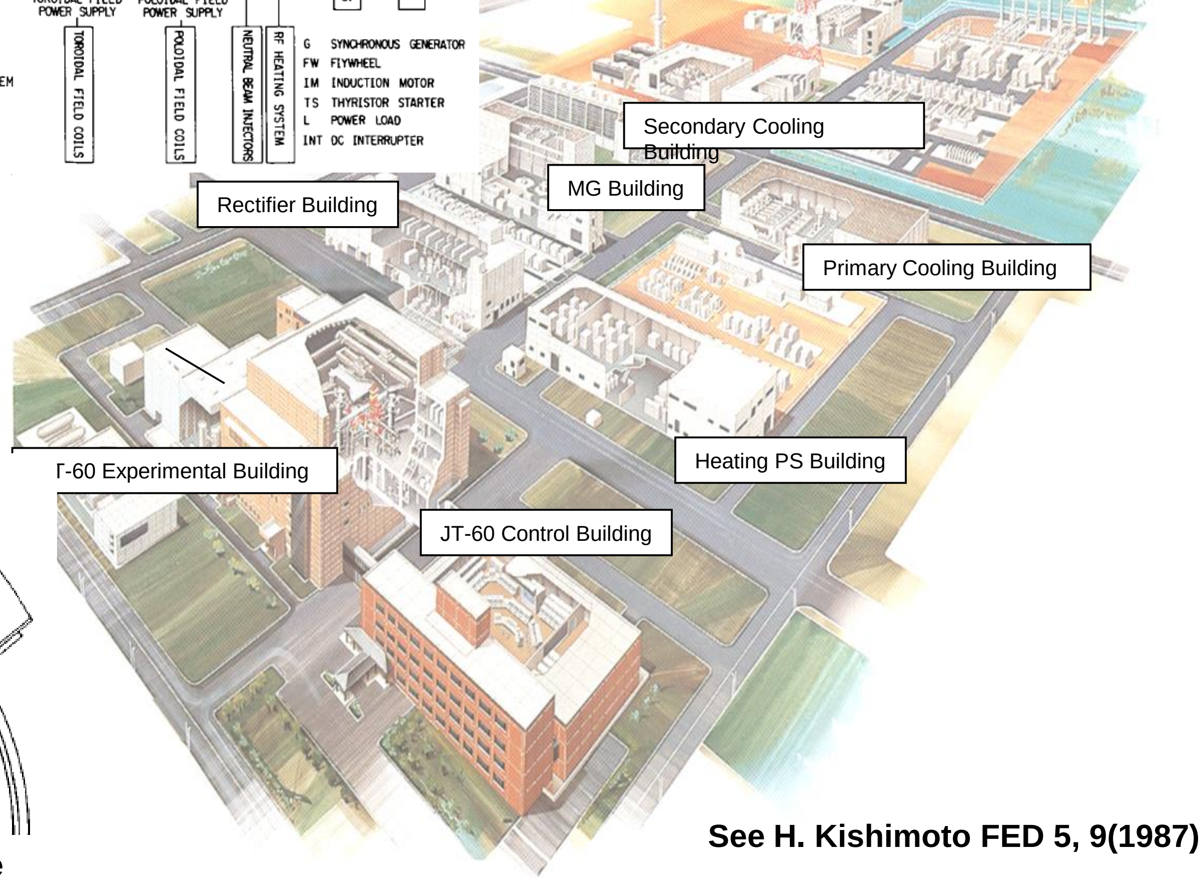
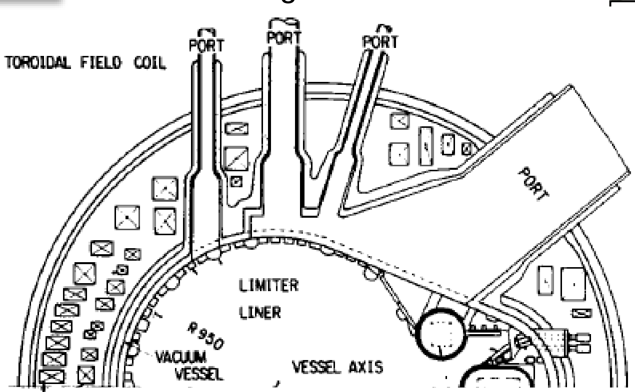




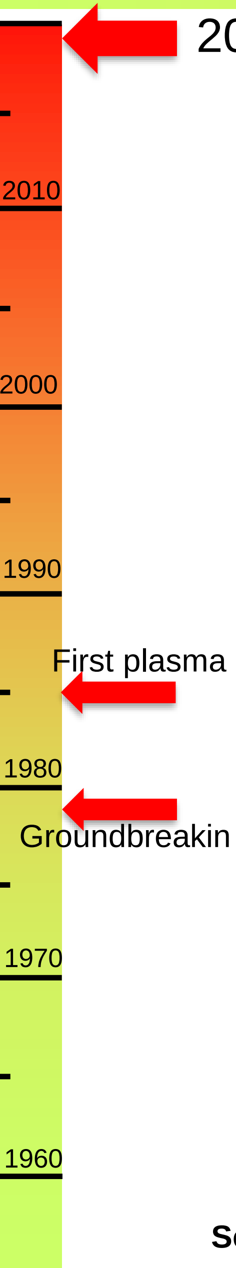




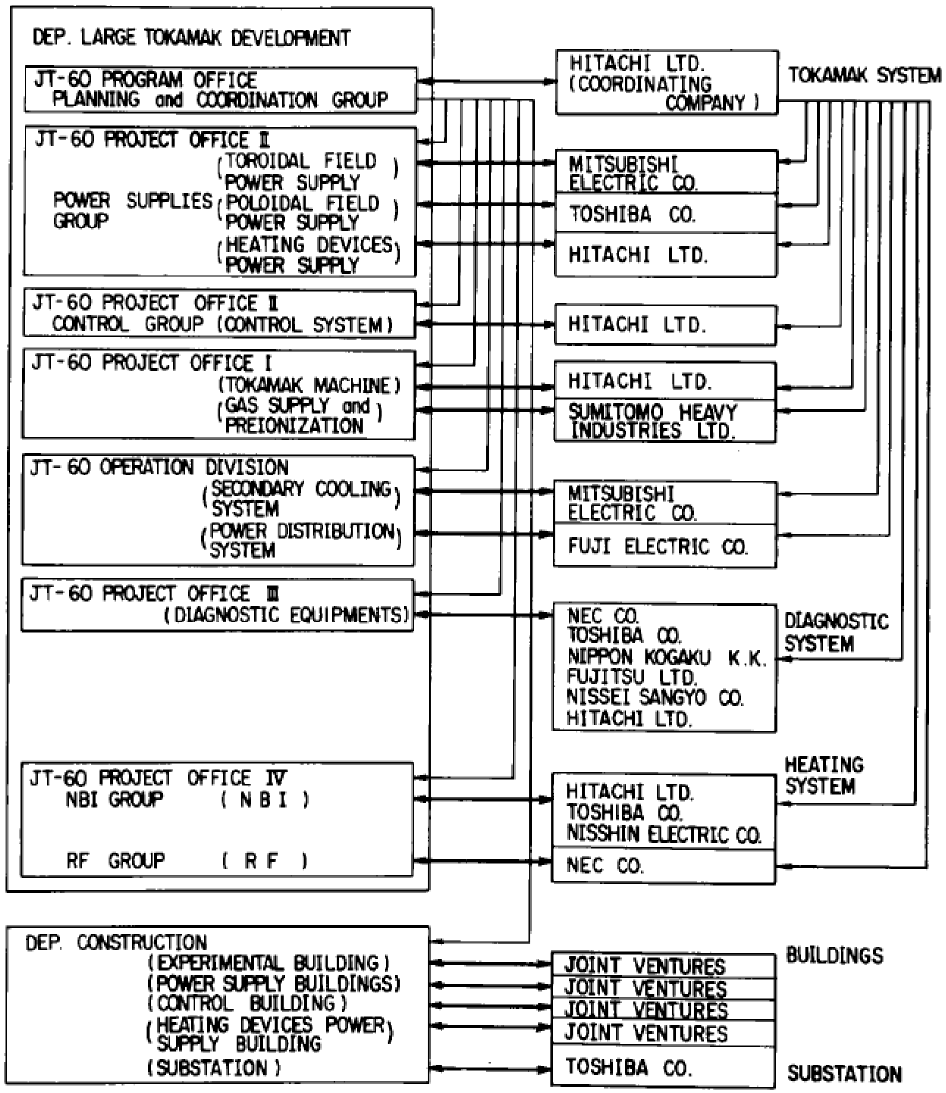
Original JT-60 : X-point outside

See H. Kishimoto FED 5, 9(1987)

2. JT-60 device construction 1978-1985



Project structure of JT-60



See H. Kishimoto FED 5, 9(1987)

H. Kishimoto: ref. [1] in my EPJH

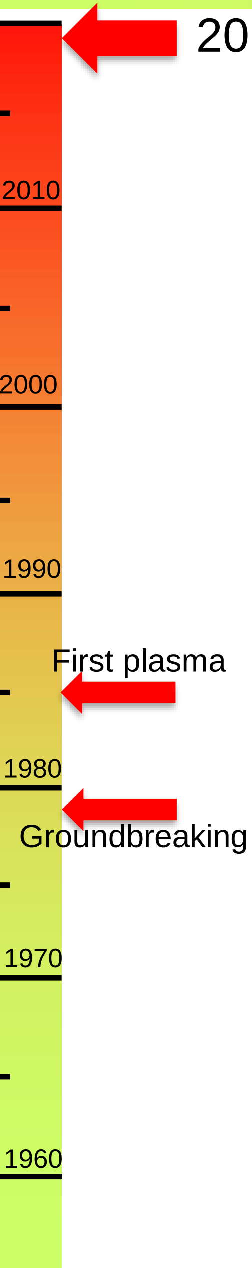
Permanent staff: JT-60 ~100 but was supported by many industrial staffs
Cf. JET~400, TFTR~900

Project control: JT-60 Program office

1. Construction plan & control
2. Control of design changes
3. Safety control (radiation, fire, earthquake, laser, RF, vibration, noise, magnetic field, water disposal, mist, power protection, interlock, emergency, labor safety, etc.)
4. Transport control
5. Quality control
6. Integrated test plan
7. Interface control between building and facilities

- Biggest task during construction was schedule control
- Most complicated task in early half of construction project was 7.

2. JT-60 device construction 1978-1985



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H. Kishimoto: ref. [1] in my EPJH
He led project control but has 3-4 members.

System integration

a) Power system

- Power supply system : Ryuichi Shimada
- System analysis : Toshiba
- Constraint on frequency & voltage stability in power grid takes ~6 years to agreement [TFC:160MW effective power, half from line and half from MG].
- High frequency filter condenser (transient use)

b) Grounding system

- Personal safety, Component protection, Signal quality (noise control)
- Optical fiber for noise control
- One point grounding
- Isolated transformer, optical coupler for phone, insulation joint for water pipe.
- Lightening rod

c) Control system

Transport of heavy components

- Need approval of 14-15 gov offices
- Weight limit of bridge and road
- ~100ton x 40-50 times from Hitachi sea port to Naka site (~20km)
- First one was P-MG made by Toshiba
- Diameter of flywheel was 5.5m from road condition as well as others.

Integrated Check and Reviews
Information from Fugen (K. Tomabechi)

- M. Yoshikawa(JAERI,Chair), E. Shoyama(Hitachi, vice chair)
- a) Interface check (262 items), b) Design and manufacturing review (136items), c) Field confirmation(296items)

JT-60 made many modifications during 23 years. For any modifications, this integrated check and review works well to reduce troubles.

Integrated Functional Test
- Individual sub-system test, linkage test, control system linkage test (1 year), integrated control system test (connect all subsystems to central control system), power test of T&P coils(started Dec. 1984).

2. Fight to achieve Breakeven in JT-60

1985.04 First plasma

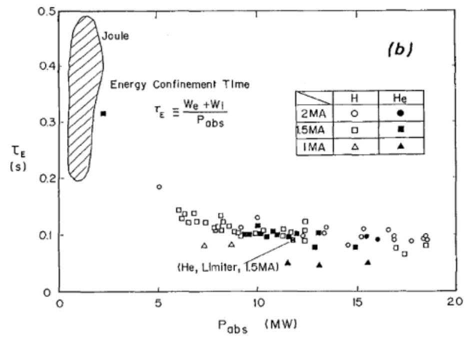
A. Kitsunezaki (1984) chaired committee on future plan with an optimistic view of achieving break-even with 20 MW NBI.
[Doublet III H-mode is believed as it recovered power degradation.]

After return from TFTR initial NBI experiments, I proposed major modification will be needed.

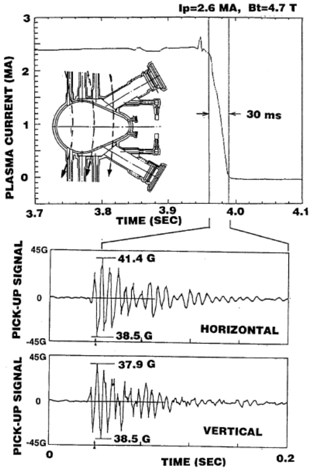
M. Yoshikawa told me that we should do our own experiments what happens.

Farewell party at Princeton, 198

First plasma in April, 1985 was start of another struggle.
AEC-J target must be achieved in 1988.
April-June, 1985 : Initial Ohmic experiments
- Installation of heating system –
July, 1986: NB Injection experiment started.
- Typical L-mode confinement -
[… conference (M. Yoshikawa)



Some initial observations
1.Plasma Disruption produces MeV runaway electrons, which hits first wall (TiC/Mo) and produced photo neutrons.
2. Plasma Disruption produces 40G acceleration and the vacuum leaks happened.



2. Fight to achieve Breakeven in JT-60

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2010
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1988
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First plasma
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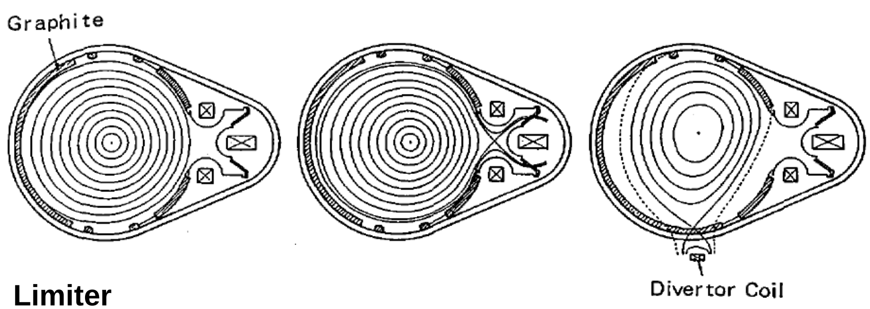
AEC-J target must be achieved in 1988 (even equivalently).

H. Kishimoto has to make plan to achieve JT-60 target regime (>5keV, $n\tau_E$>2 x10^{13}cm^3 s).

1. **Place divertor coil below vacuum vessel to produce Lower X-point**
   Only 6 months to install (1987-1988)
2. **Increase B_t=4.5T-> 4.8T, and I_p=2.1MA->2.7MA(Div), 2.7MA->3.2MA**



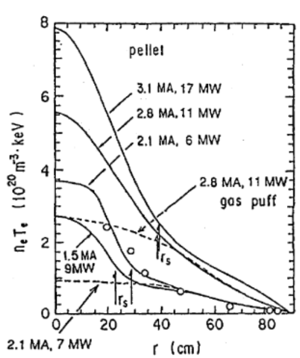
Limiter
2.7MA-> 3.2MA
Bt=4.5T-> 4.8T

Outer divertor
2.1MA-> 2.7MA

Lower single null
2MA

Oct. 1988: IAEA Nice conferenc
(H. Kishimoto)
$n_e(0)\tau_E Ti(0)$=6 x 10^{19} m^{-3} s keV

3. **Installation of high speed pellet injector 2.3km/s, 4 pellets**



Oct. 1990: IAEA Washington conference
(M. Nagami)
$n_e(0)\tau_E Ti(0)$=1.2 x 10^{20} m^{-3} s keV

It was clear JT-60 must have major upgrade

2. Fight to achieve Breakeven in JT-60

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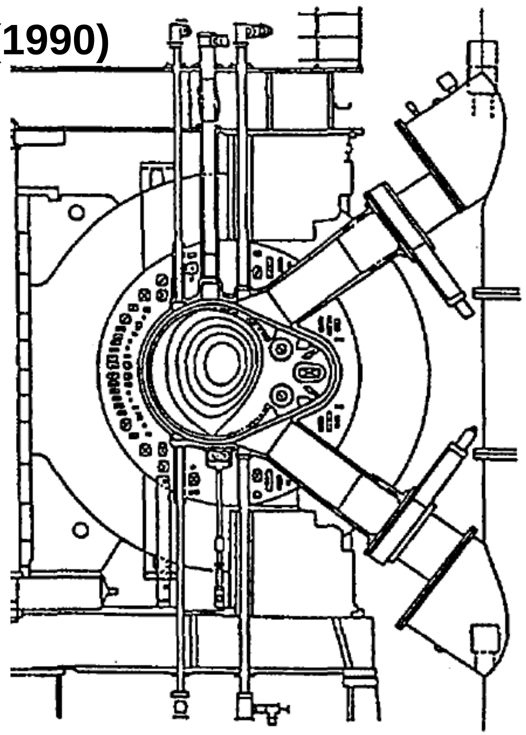
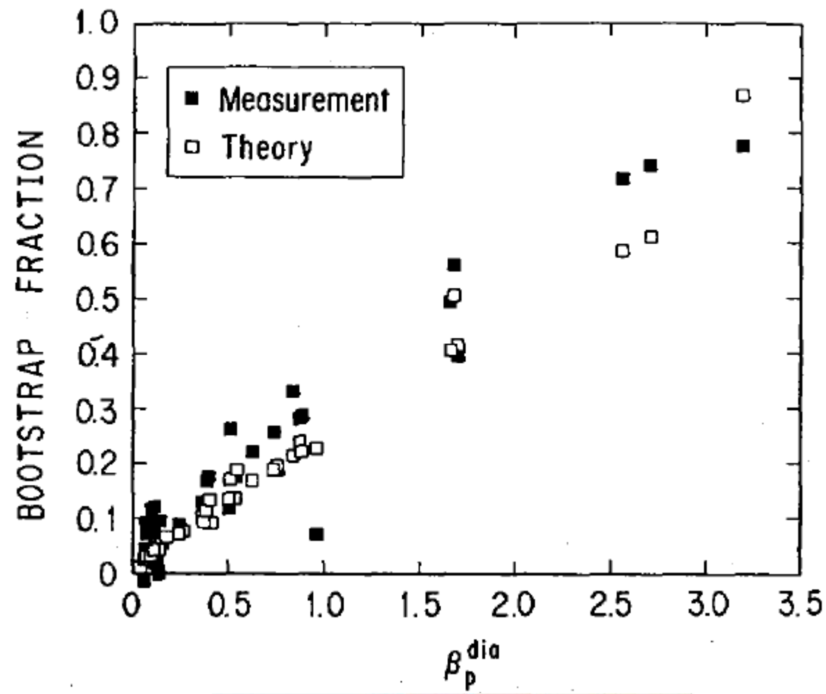
Lower X-point divertor produces "serendipity" called the high β_p regime relevant for steady state tokamak operation. It demonstrated ~80% bootstrap current fraction.

M. Kikuchi, NF, 30, 343(1990)

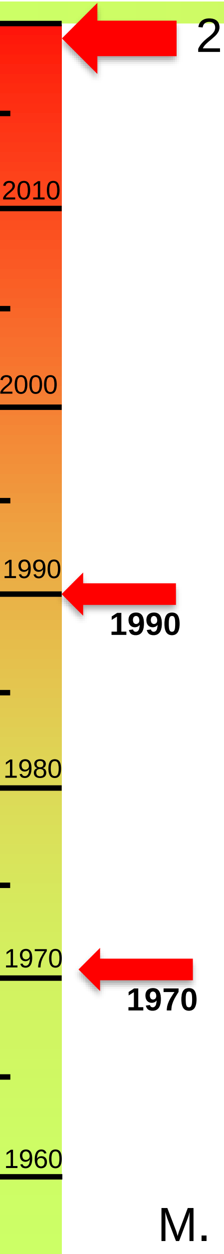


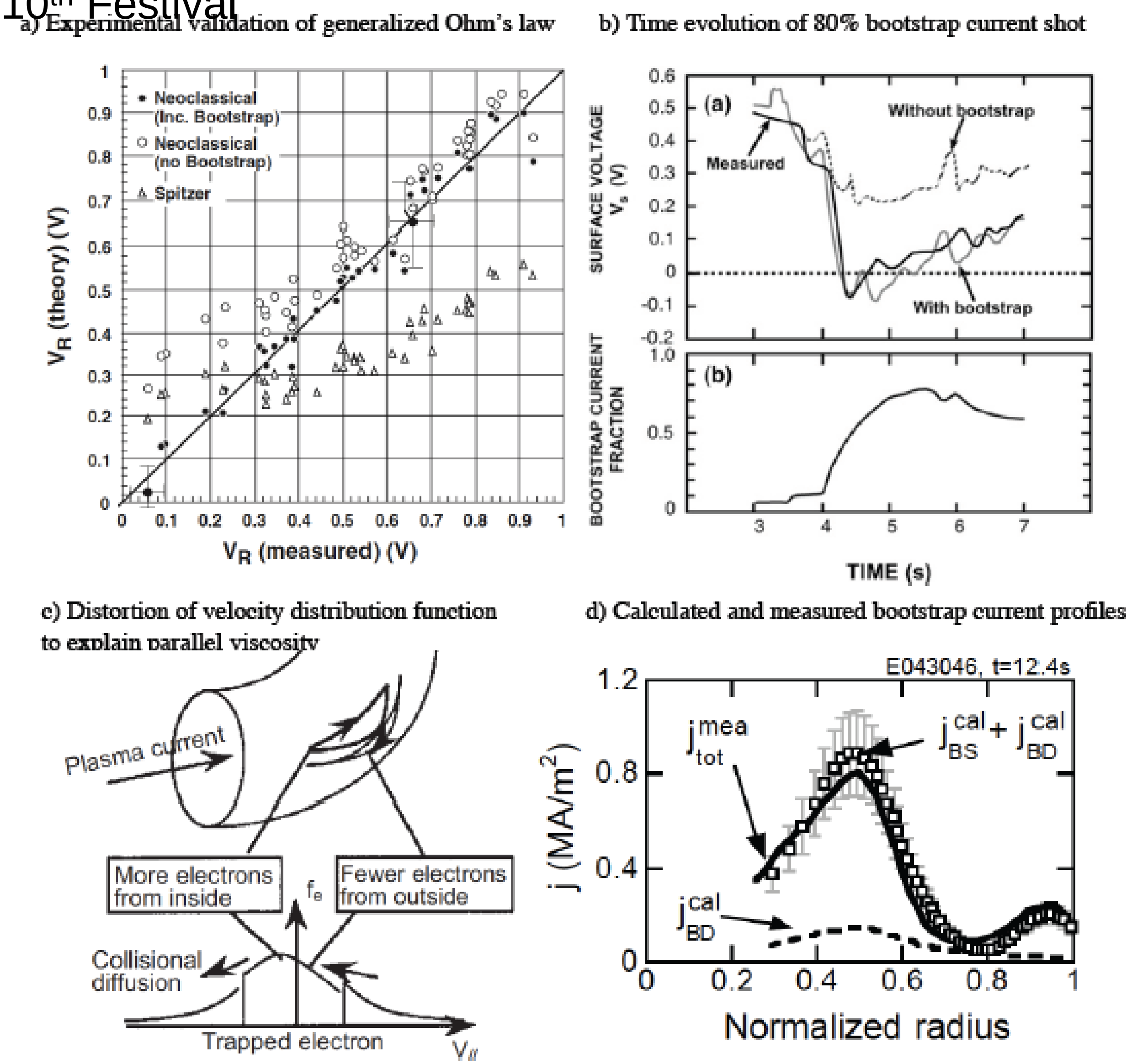


Read my Rev. Mod. Phys. 2012 for details.

Galeev 1970, Bickerton 1971

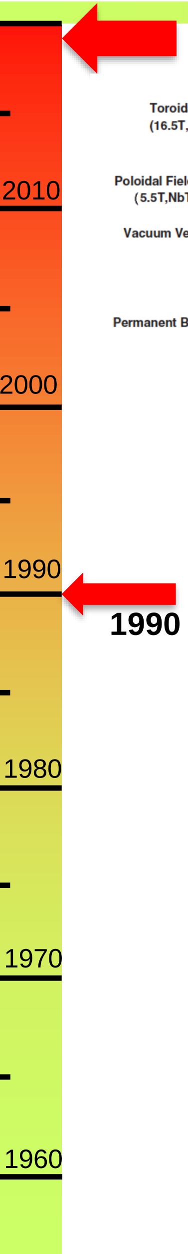
2. Generalized ohm's law confirmed as well as Bootstrap current

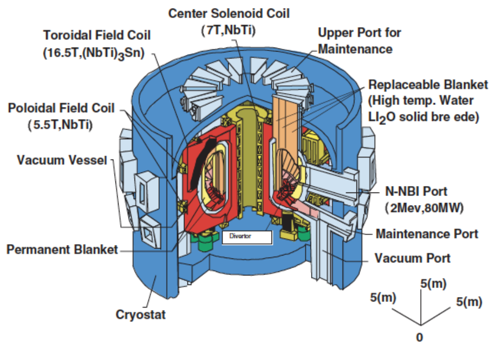


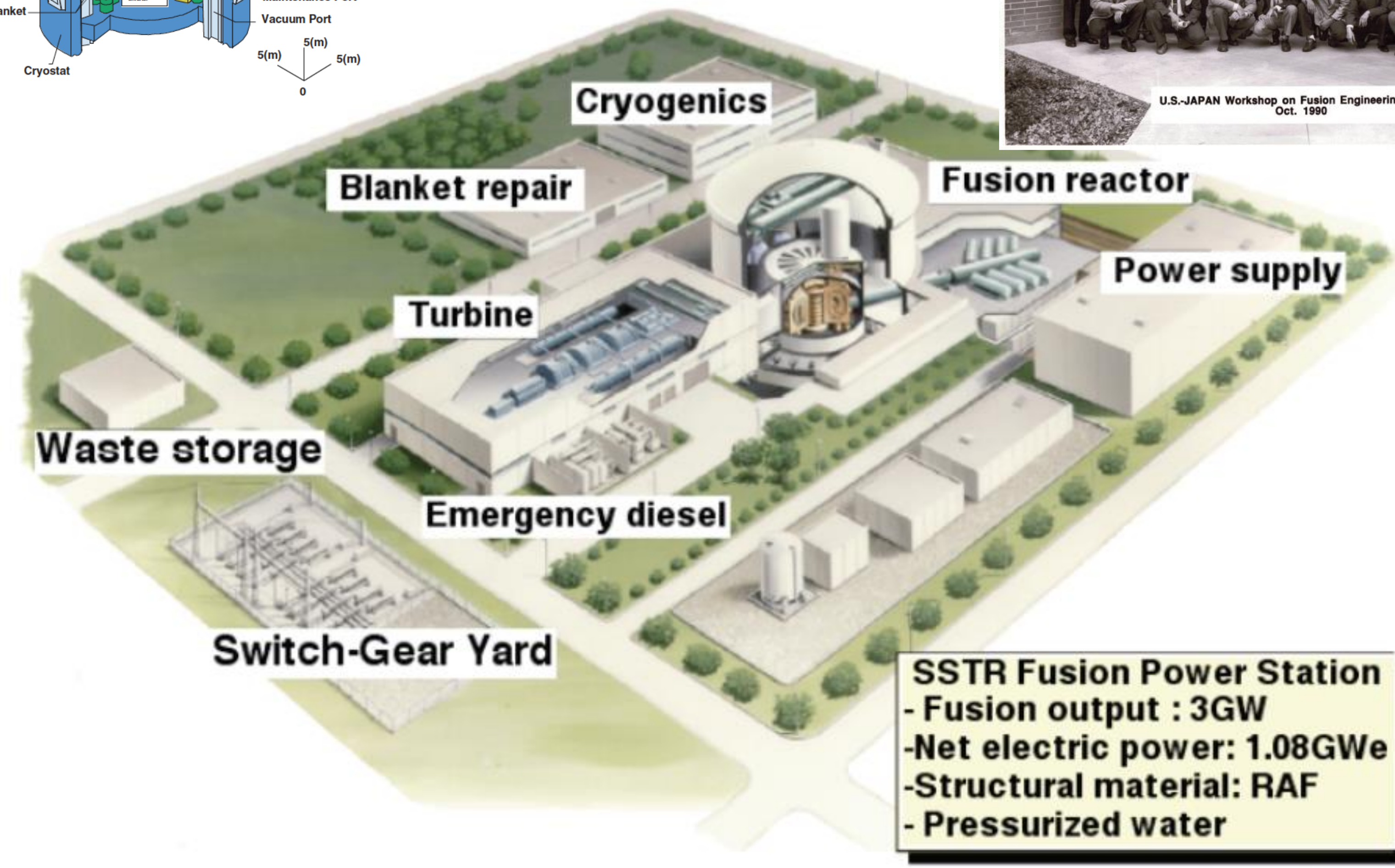


M. Kikuchi, et al., NF 30, 343 (1990), M. Kikuchi, M. Azumi, PPCF 37,1215 (1995)

2. JT-60 high bootstrap current achievement led to SSTR design

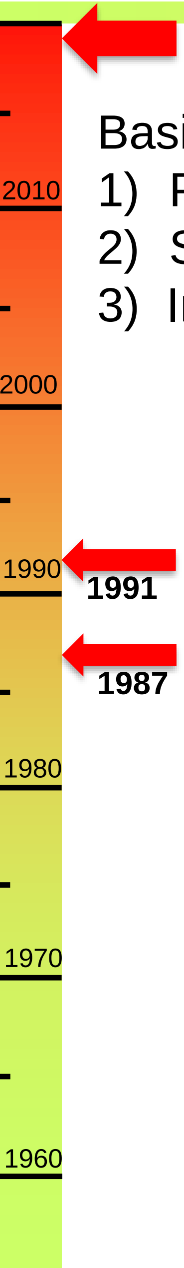






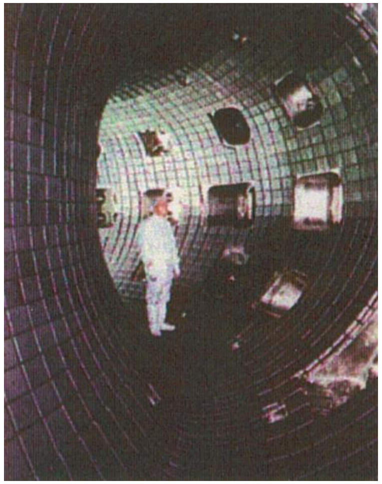
SSTR Fusion Power Station
- Fusion output : 3GW
- Net electric power: 1.08GWe
- Structural material: RAF
- Pressurized water

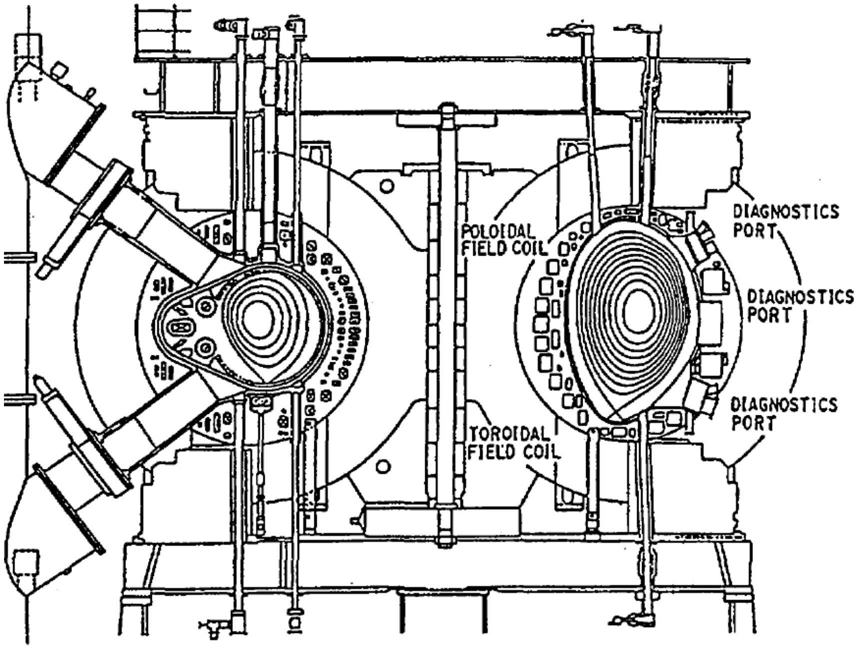
2. Fight to achieve Breakeven in JT-60



Basic design :April – Sept. 1987 M. Kikuchi (ordered by H. Kishimoto)

1) PFC feeder for assembly,
2) Stress limit at PFC joints (M. Matsukawa)
3) Inconel VV (H. Horiike and H. Ninomiya)





JT-60 to JT-60U modification

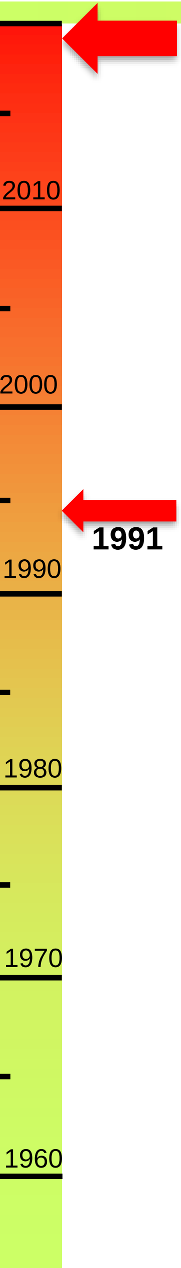
JT-60 was hydrogen machine.
Use of Deuterium is not allowed.
S. Seki handled D use and safety.

H->D : NBI power was doubled 20MW->40MW

late 1988 : Contract to Hitachi

Nov.1989 : Shutdown JT-60
3 months completed :Disassembly
1990.03 : VV(MHI) arrival to Naka

2. JT-60 discovered ITB (Internal transport barrier)



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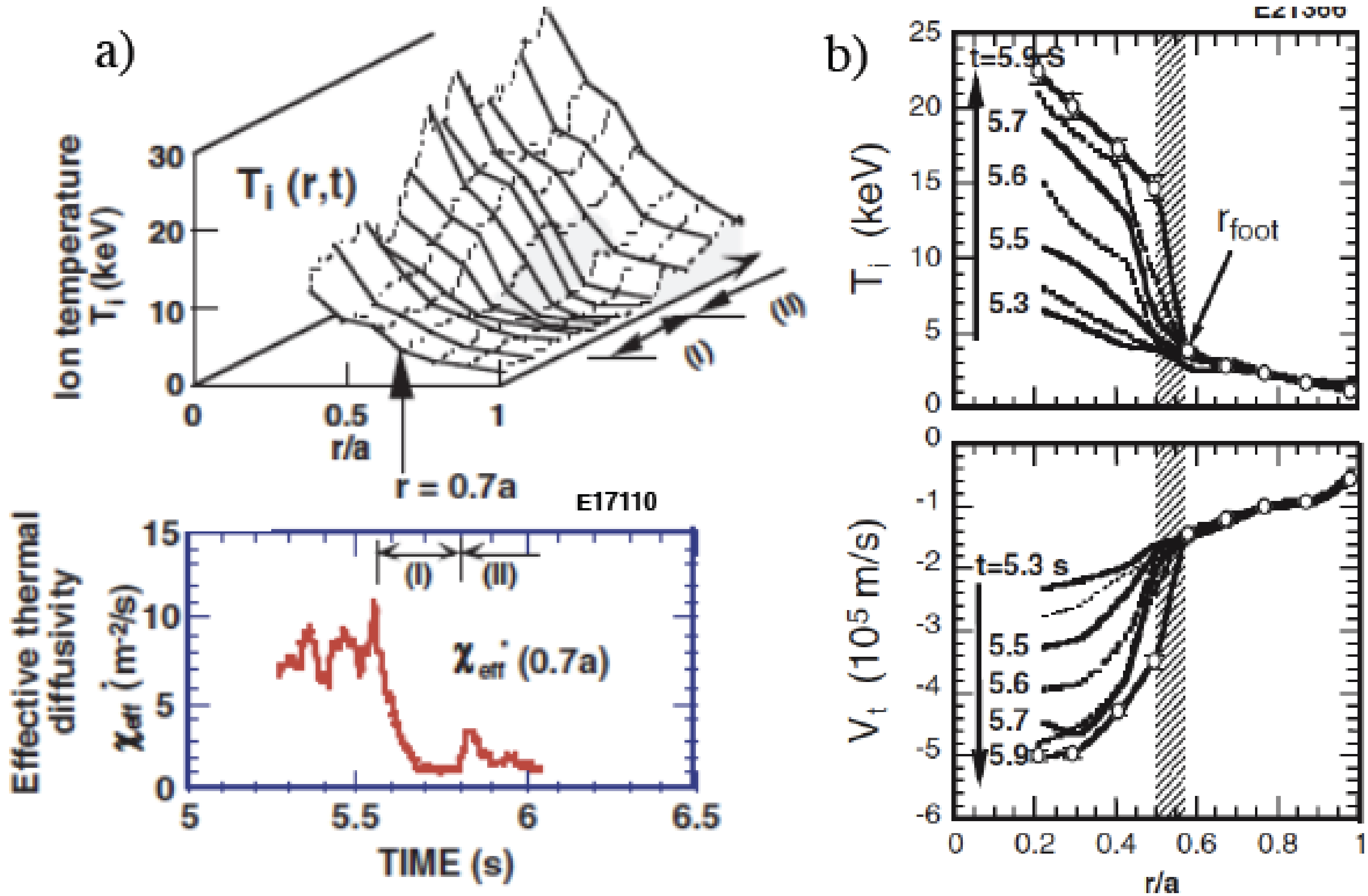
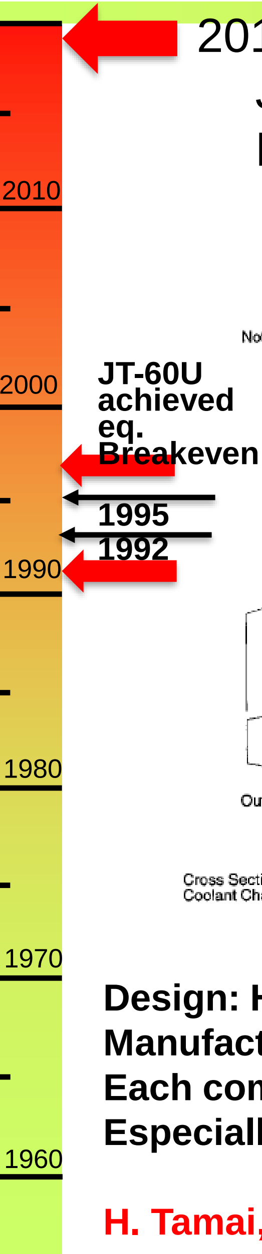
Y Koide, M. Kikuchi, et al., PRL1994, PPCF1994, Koide, FEC1994



In April 1994, I moved planning office to control 100M$ annual budget for JT-60U

2. Big project always face difficulties: I Water leak from TF coil



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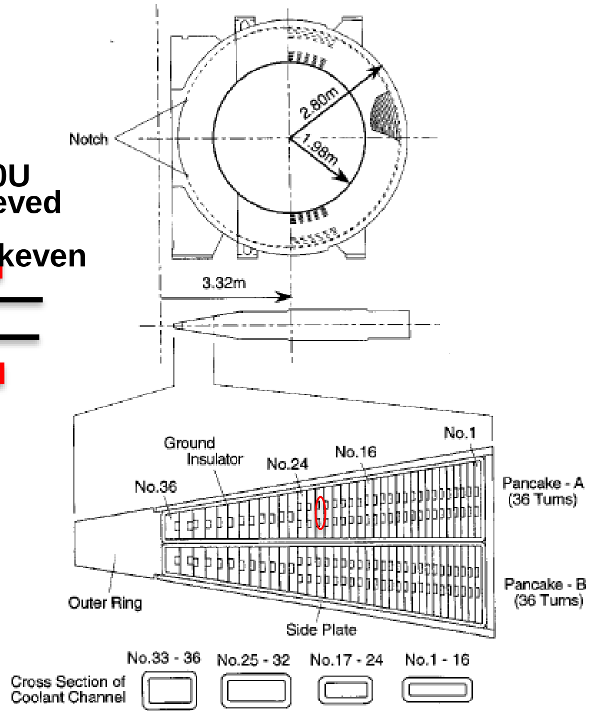
JT-60 TF magnet

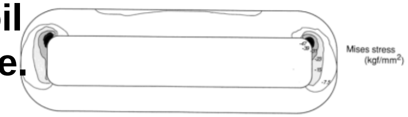
B_{max}=10T, W_{mag}=2.8GJ



Serious problem:

Oct. 1992: Water leakage from #9 TF coil

Cause: crack in the corner of water pipe.



June1995: Water leakage from #14

We could operate stopping water in one of two channel

Even more serious problem:

Dec. 1995: Water leakage from #9 same conductor another channel

No cooling of conductor!!

JAERI Vice president asked cause and safety assessment to approve restart JT-60U.

Cu-Insulator system: difficult to quantify

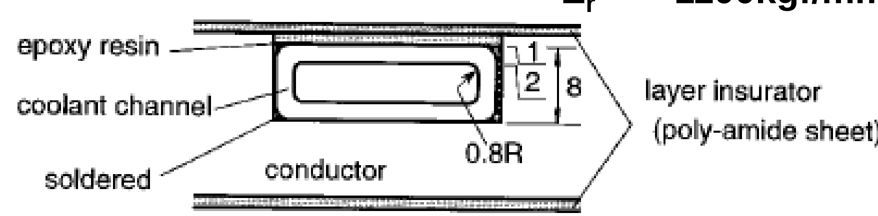
Young's modulus E was different

$$E_r^{\mathrm{equiv}} = (L_r^{\mathrm{Cu}} + L_r^{\mathrm{Ins}})/(L_r^{\mathrm{Cu}}/E_r^{\mathrm{Cu}} + L_r^{\mathrm{Ins}}/E_r^{\mathrm{Ins}}),$$

E_r^{Ins} significantly smaller than design (4-20 times) did not have problem. Reason: Almost no radial force transmission.

E_r^{Cu}=11000kgf/mm^2

E_r^{Ins}= 1100kgf/mm^2



Design: Hitachi

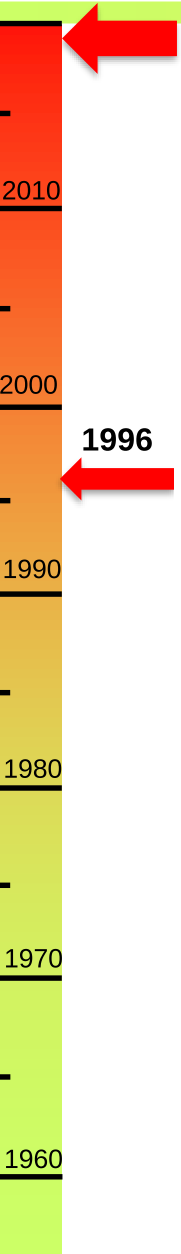
Manufacturing: Hitachi and Toshiba

Each company has their own know how.

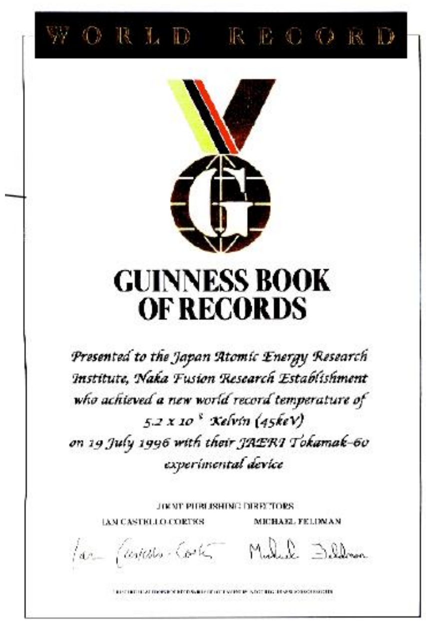
Especially insulator and impregnation method.

H. Tamai, M. Kikuchi, --,Toshiba, Hitachi, FED199

2. Big project always face difficulties: I Water leak from TF coil



After taking all countermeasures on safe TFC operation, restart of operation was approved by JAERI's Vice President Kenichi Murakami (an expert of nuclear system safety) in January 1996. The 1996 JT-60U operation started with a longer shot interval but made immense advances in plasma parameters. World records were set in ion temperature $T_i(0) = 45\,\mathrm{keV}$ (a Guiness World Record) and fusion triple product $n_i(0)T_i(0)\tau_E = 1.5 \times 10^{21}\,\mathrm{m^{-3}\,s\,keV}$. Just before the end of operation, we achieved an equivalent break-even condition $Q_{DT}^{eq} = 1.04$ with the energy confinement time $\tau_E = 0.97\,\mathrm{s}$, central ion temperature $T_i(0) = 1.9 \times 10^8\,\mathrm{K}$ and central electron density $n_e(0) = 9.7 \times 10^{19}\,\mathrm{m^{-3}}$.


WORLD RECORD

GUINNESS BOOK OF RECORDS

Presented to the Japan Atomic Energy Research Institute, Naka Fusion Research Establishment who achieved a new world record temperature of 5.2×10^8 Kelvin (45keV) on 19 July 1996 with their JAERI Tokamak-60 experimental device

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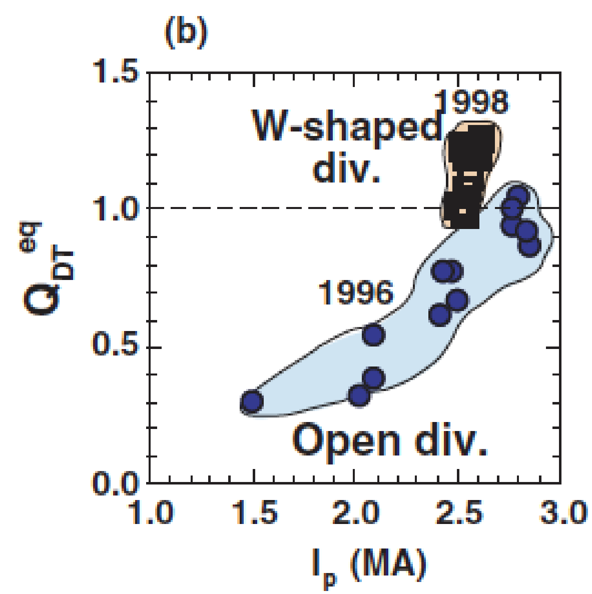

2. Big project always face difficulties: Radiation protection control

2010
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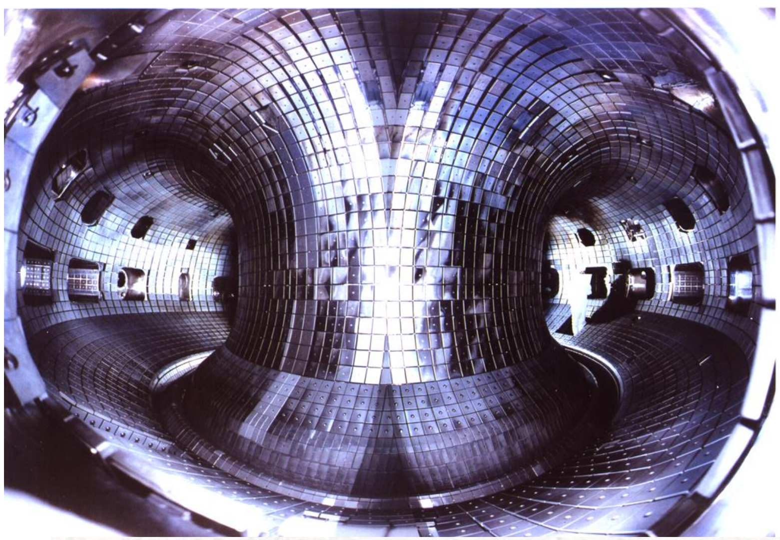
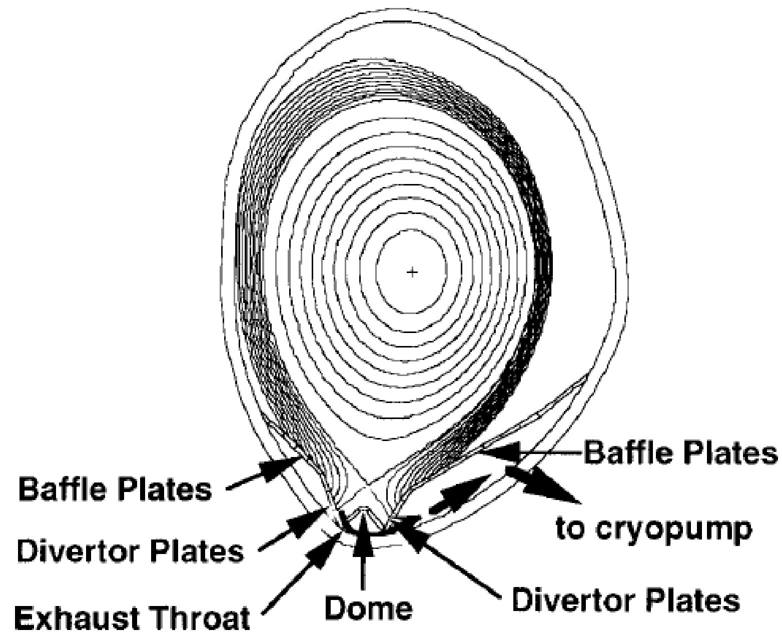
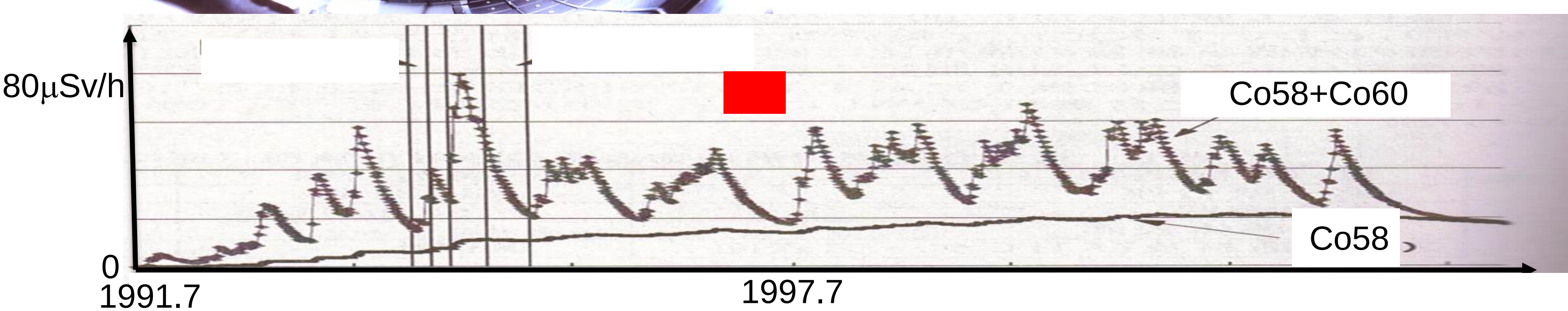
Use of deuterium in JT-60 makes long period in-vessel works more difficult.
We plan installation of W-shaped divertor in 4th quarter in 1996.
Expected integrated radiation dose for workers are expected to be top 1 in JAERI !
Radiation does in fission research reactor is much smaller than that of JT-60. It will make "Fusion" is not safe!

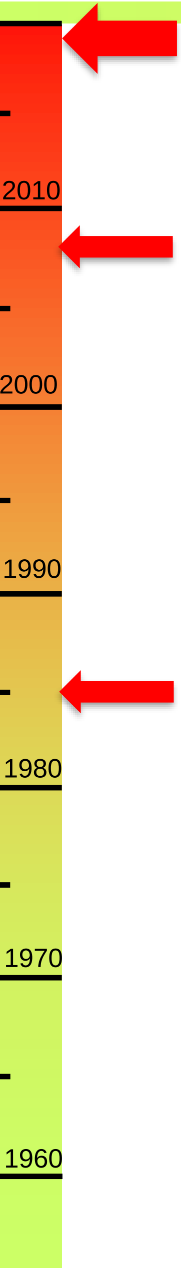
1996







2. Historical fight to achieve equivalent break-even in JT-60



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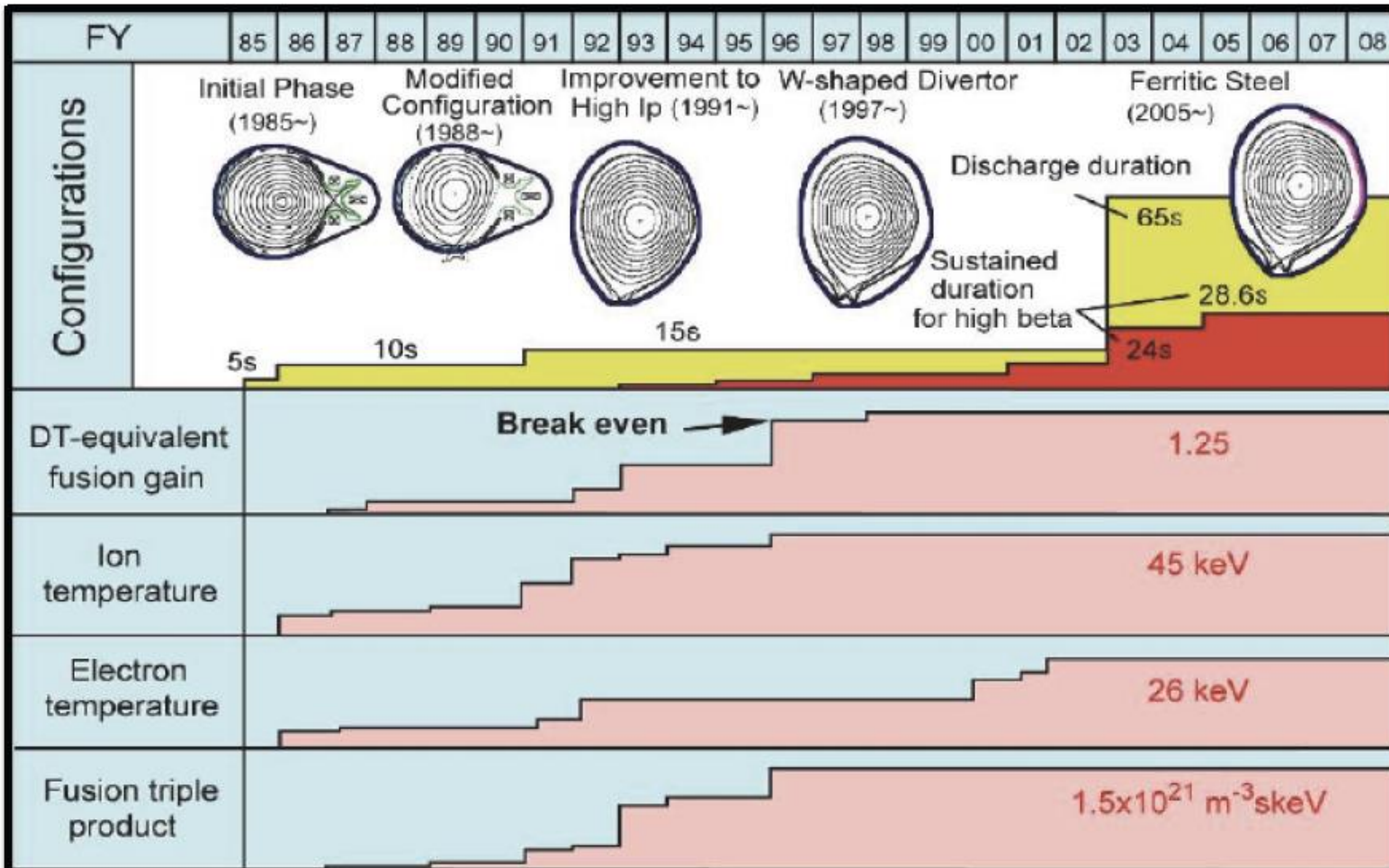
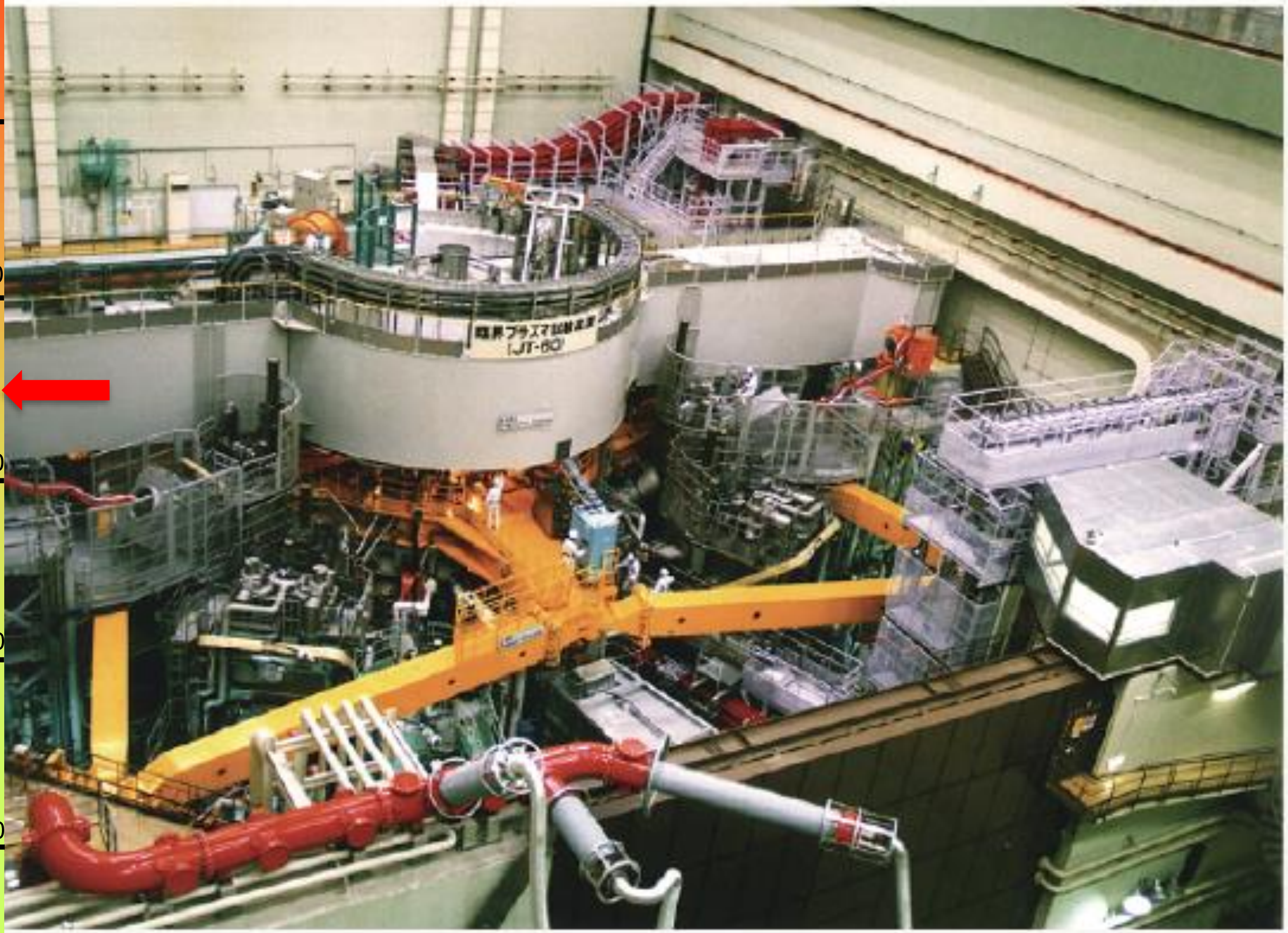


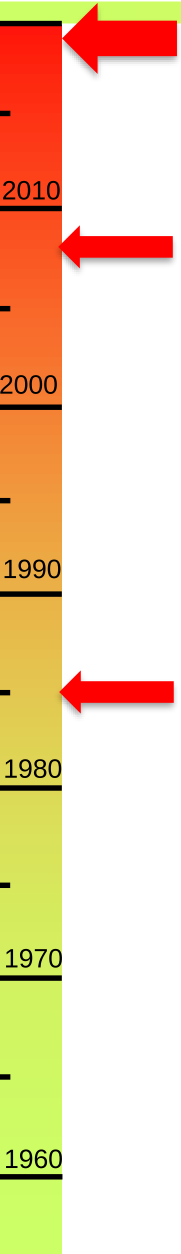
2. JT-60 hardware capability was world-leading



PARAMETERS:

- R_p=3.3 m
- $V_{ol} \leq 100\ m^3$
- $I_p \leq 5.0$ MA
- $B_t \leq 4.2$ T
- $\Phi = 61$ Vs
- $T_{dis} \leq 65$ s
- $P_{PNB} \leq 40$MW
- $P_{NNB} = 5.8$MW
- $P_{IC} \leq 7$ MW
- $P_{LH} \leq 7$ MW
- $P_{EC} \leq 3$ MW
- E_{inj}=445MJ

2. JT-60 achieved numerous records



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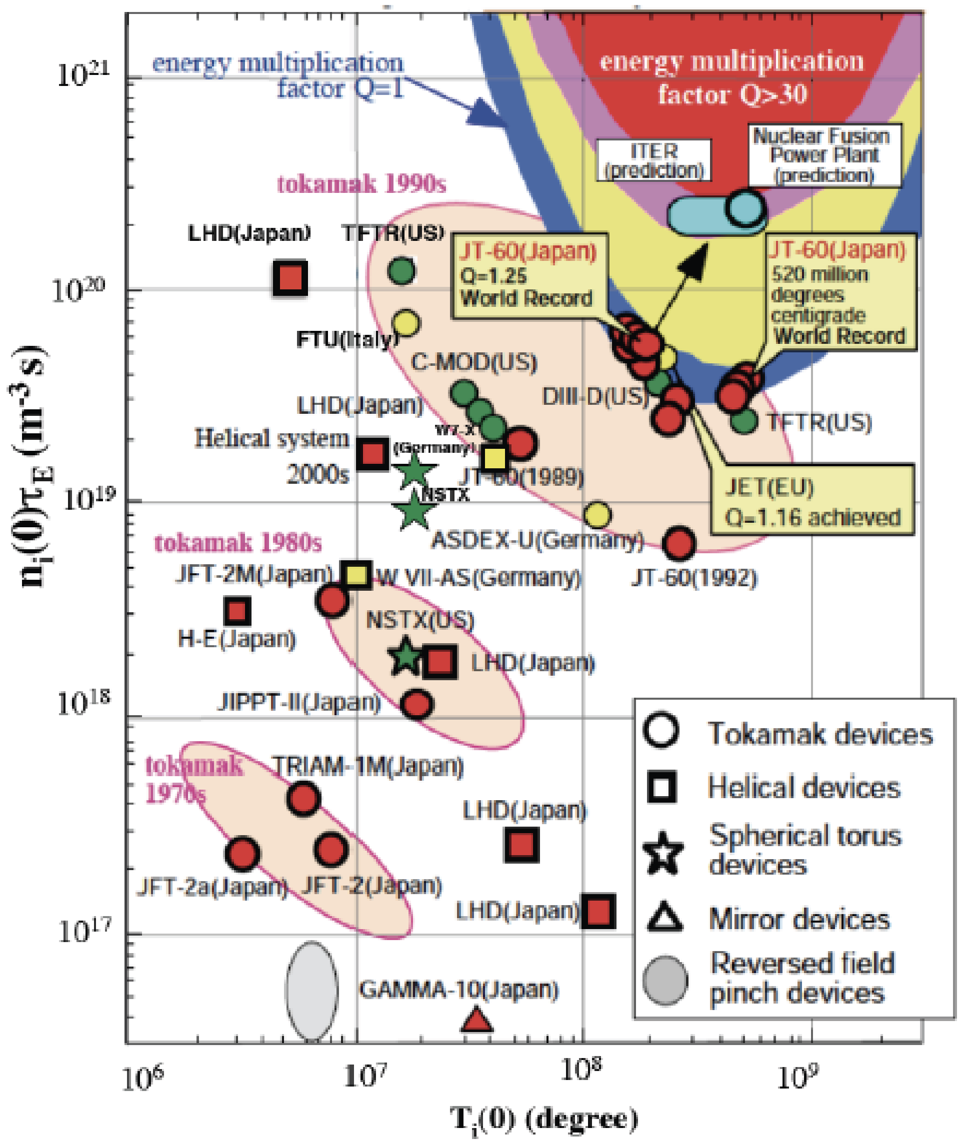


JT-60 Parameters Achieved

$Q_{DT}^{eq}=1.25$

$T_i(0)=45keV$

$T_e(0)=26keV$

$n_e(0)=2.8\times10^{20}m^{-3}$

$S_{neutron}^{DD}=5.6 \times 10^{16}/s$

$\tau_E=1.1s$

$f_{bootstrap}\sim100\%$

$I_p^{NBCD}=1MA$

$\eta_{NBCD}=1.55 \times 10^{19}\ A/m^2/W$

$I_p^{LHCD}=3.6MA$

$\eta_{LHCD}=3.5 \times 10^{19} A/m^2/W$

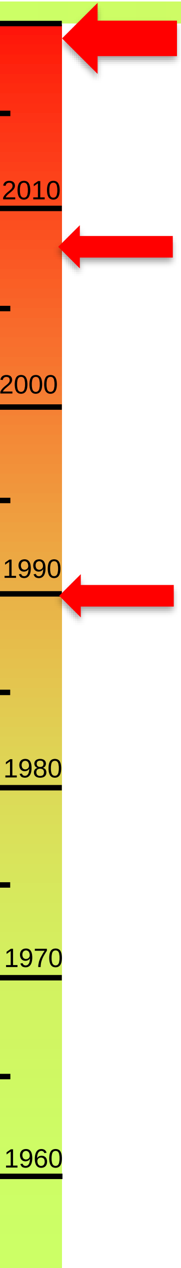
$I_p^{ECCD}=0.74MA$

$\eta_{ECCD}=0.42 \times 10^{19} A/m^2/W$

$\beta_t=2.7\%$

$\beta_p=4.7$

3. Historical fight to establish DEMO/SSTR basis



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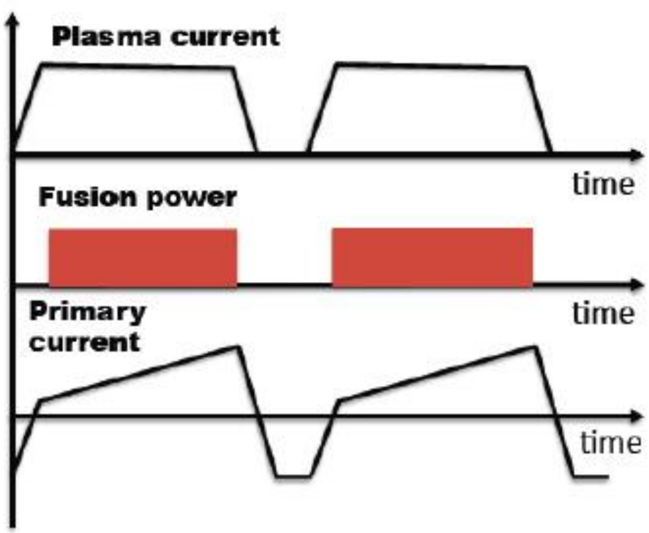
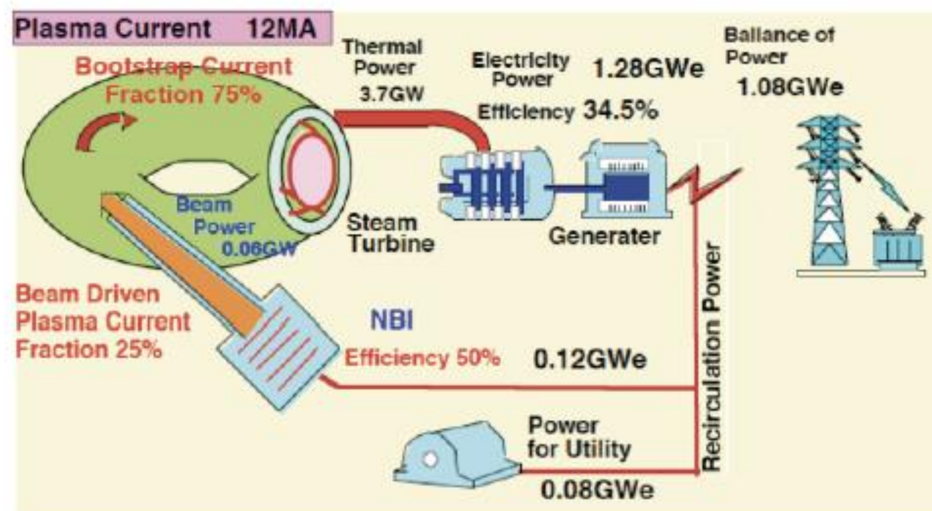
1. M. Kikuchi, M. Azumi, Reviews of Modern Physics 84,1807(2012)
2. M. Kikuchi, Frontier in Fusion Research – Physics and Fusion (2011)
3. M. Kikuchi, M. Azumi, Frontier in Fusion Research II – Introduction to Modern Tokamak Physics(2015)

R. Conn and A. Guth(2015)

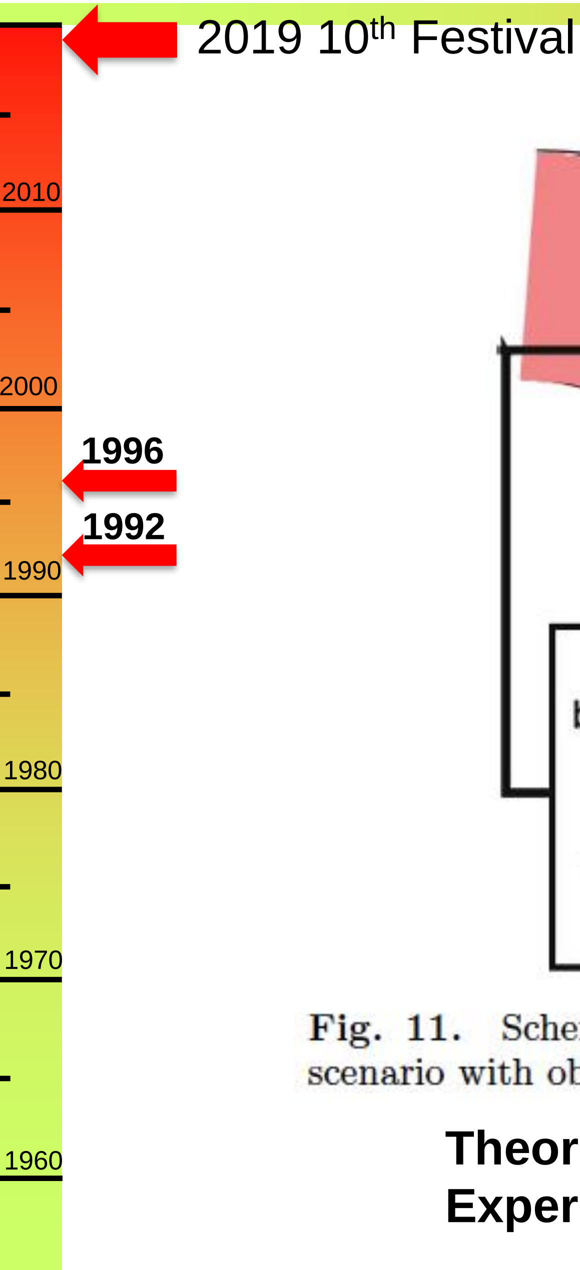
a) Inductive Operation



b) Principle of Steady State Tokamak Reactor



3. Advanced Tokamak Physics: Negative shear operation



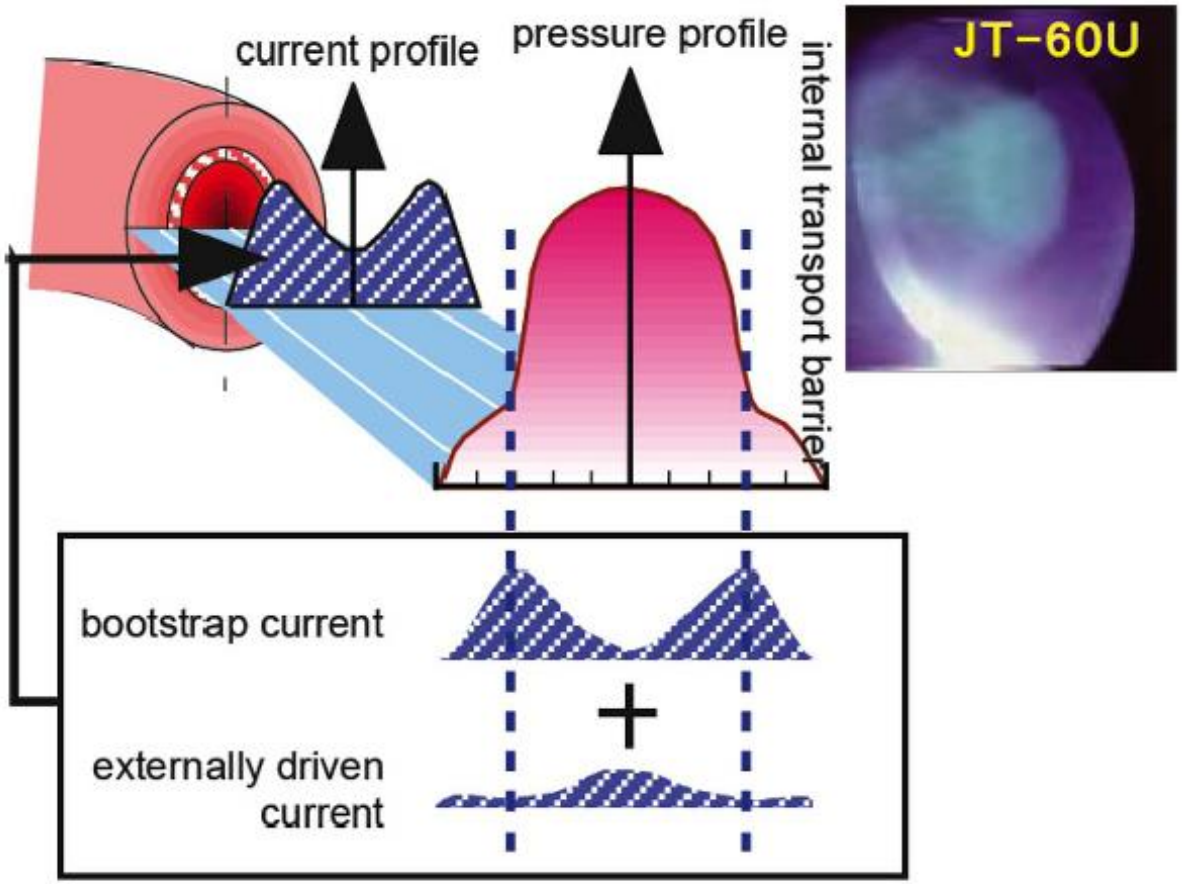
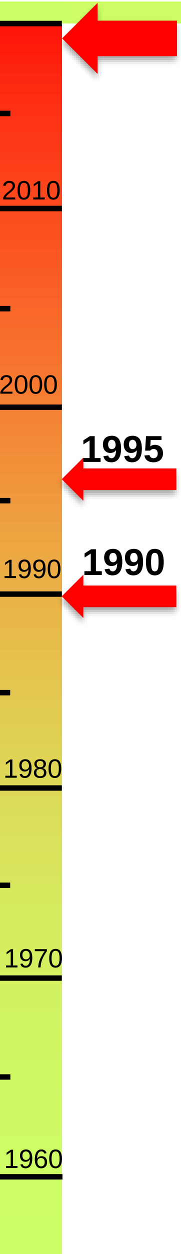
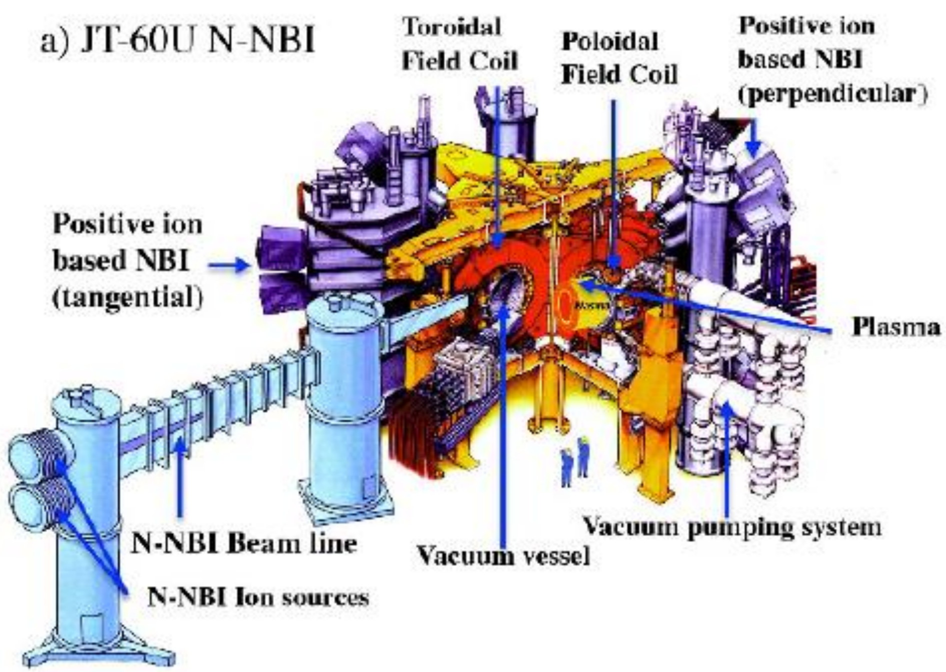


Fig. 11. Schematics of current and pressure profiles in the negative shear operational scenario with observed visible TV at the high density core of JT-60U.

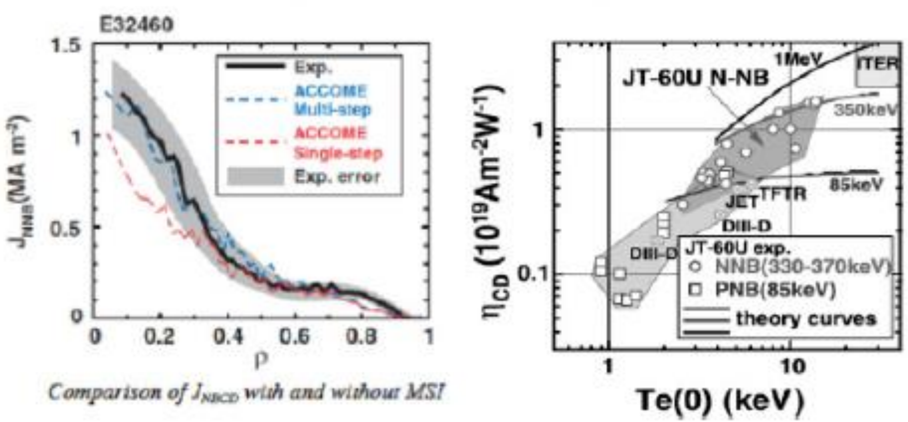
Theoretical prediction: Ozeki, FEC1992
Experimental Q=1 with NS: Fujita, FEC1996

3. Advanced Tokamak Physics: Negative-ion-based NBCD





b) Driven NBCD profile and its efficiency



100% bootstrap drive is possible but may not good for control.

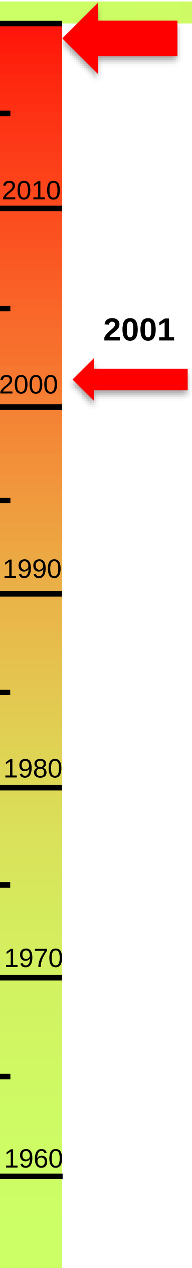
Which could be reactor current driver?

Our choice was NBCD.
See SSTR design (1990).

To develop NBCD, we decided to implement 500keV NBCD system in JT-60U.

First result was published in 1995 (FED).

3. Advance Tokamak Physics: AE modes



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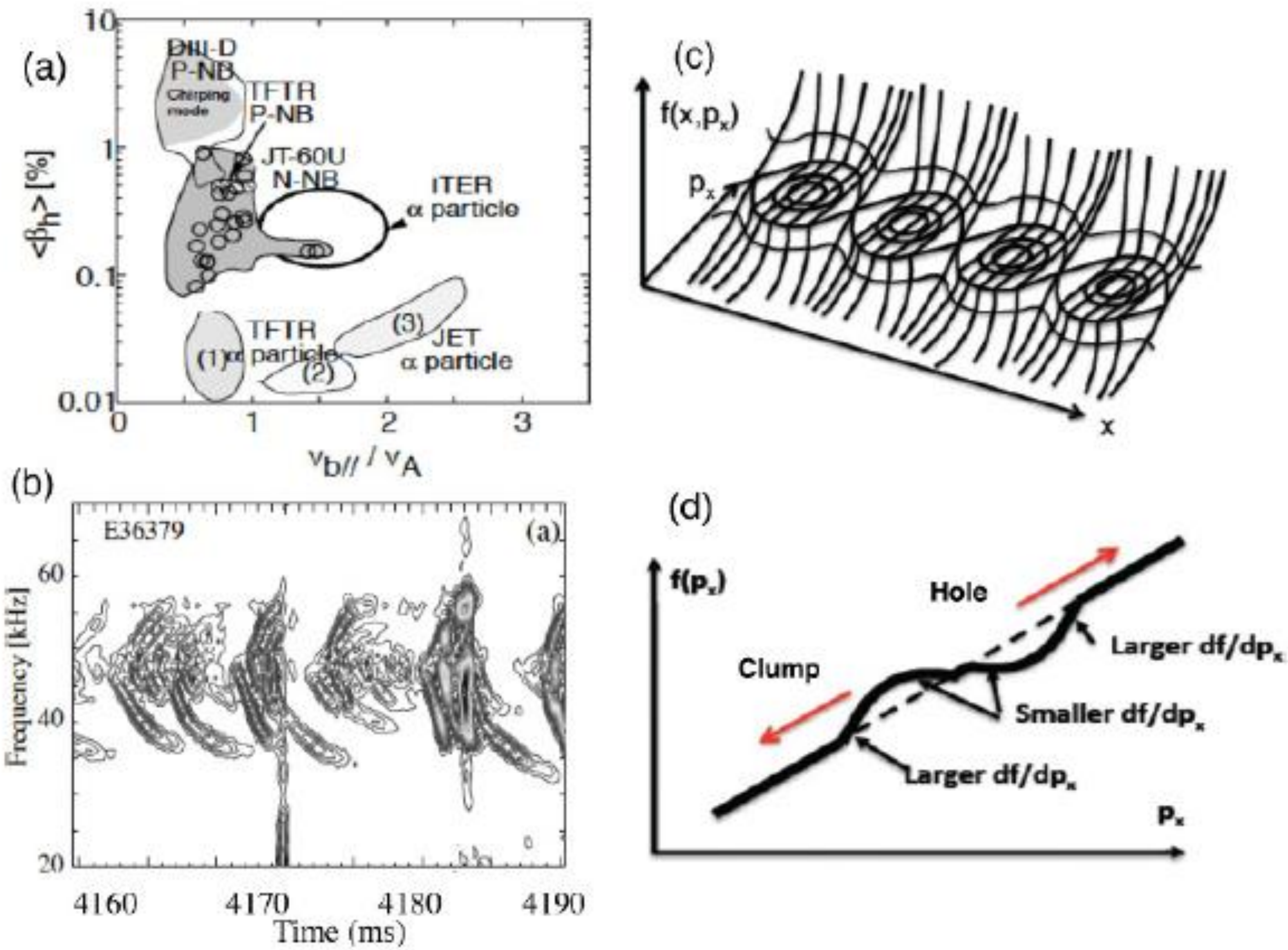
N-NBI provided rich set of discovery in AE physics. Kramer PRL1998(NAE), Kimura(RSAE),Shinohara NF2001(BB mode), Lesur PoP2009



3. Advanced Tokamak physics: Flow shear suppression and de-correlation

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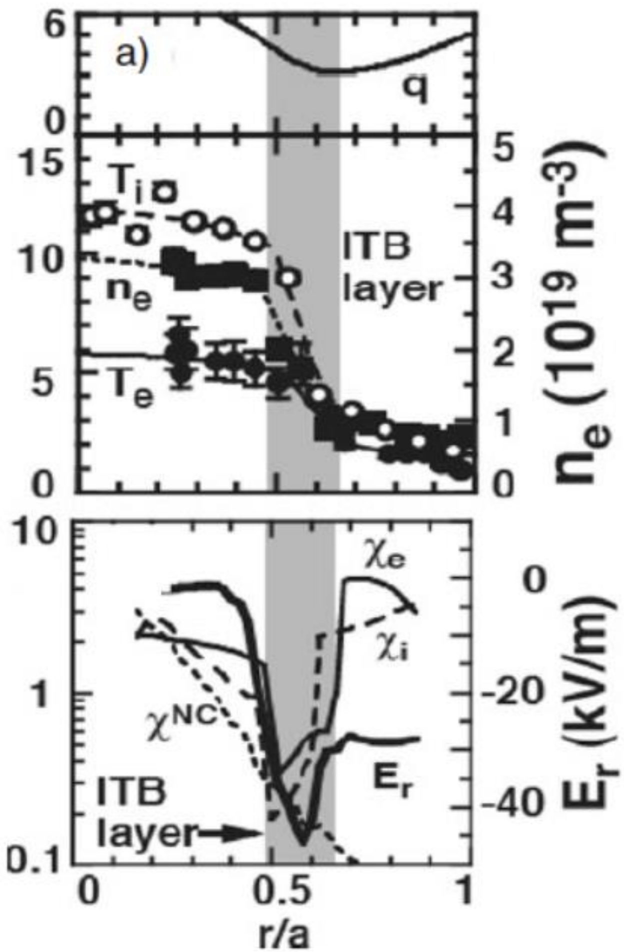
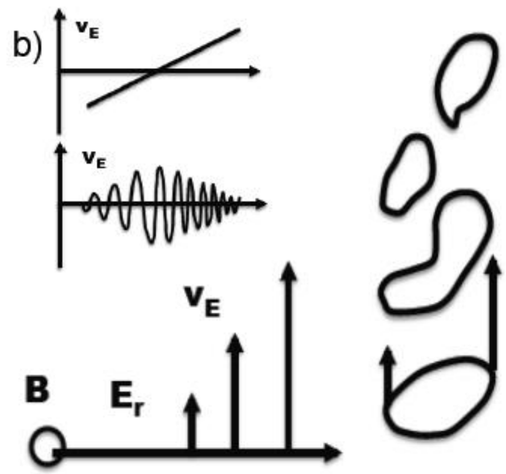
1998

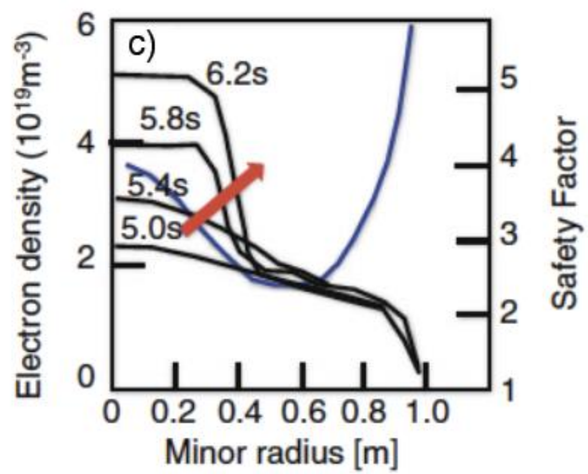
Head of Analysis division

My formulation to calculate Er is implemented to TOPICS code.



H. Shirai, M. Kikuchi, NF1999





Nazikian, PRL2005

Flow shear suppression of turbulence

Biglari-Diamond-Terry PF1990

TH Dupree, PF1972

3. Advanced Tokamak physics: Current Hole Discovery

2019 10th Festival

2010

2001

2000

1990

1980

1970

1960

Fujita PRL2001 observed "Current Hole"

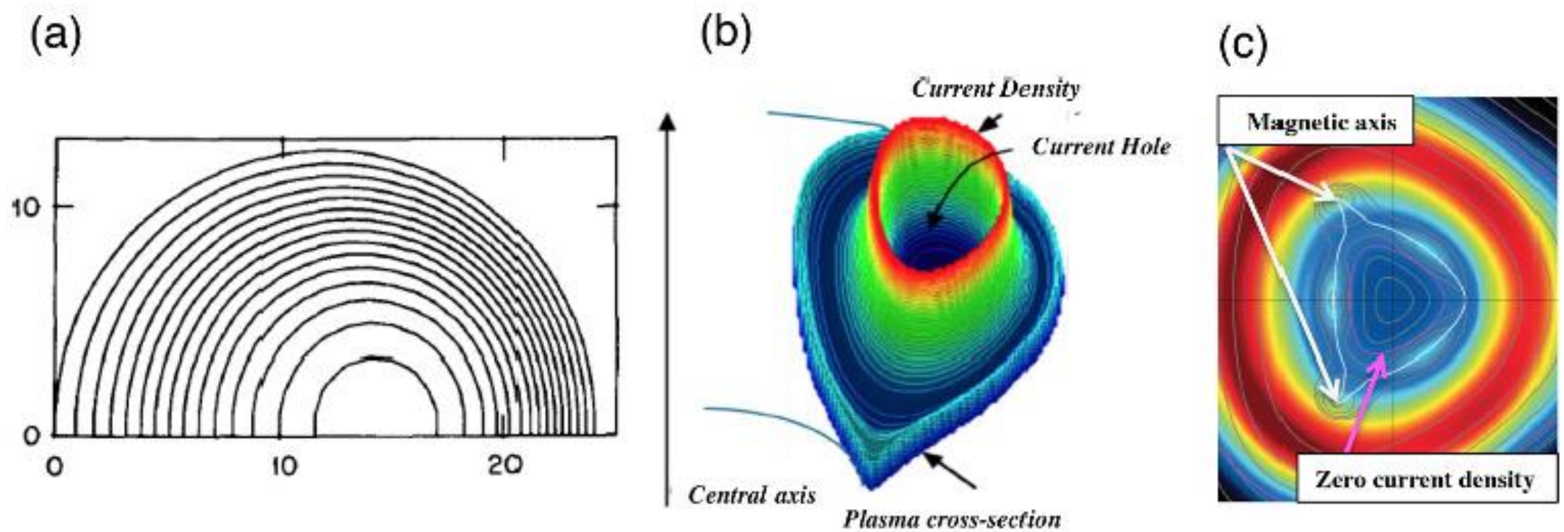
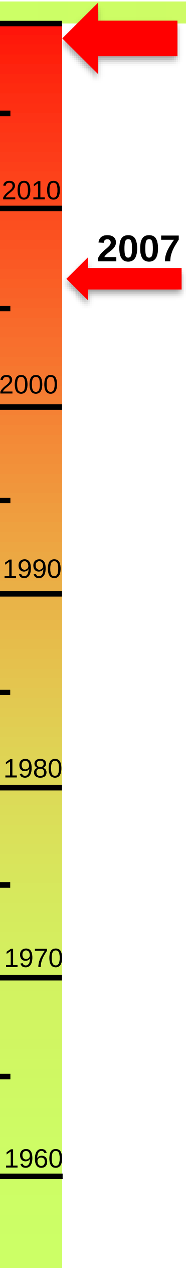


Fig. 12. (a) Schematics of nested flux surface equilibrium. (b) Schematics of current hole equilibrium obtained in JT-60U with almost no current in the central region of plasma column [50]. (c) Bifurcated non-nested flux surface equilibrium. Inside the zero-current density surface (magenta), current density becomes slightly negative [55].

3. Advanced Tokamak Physics: Resistive wall mode stabilized by rotation



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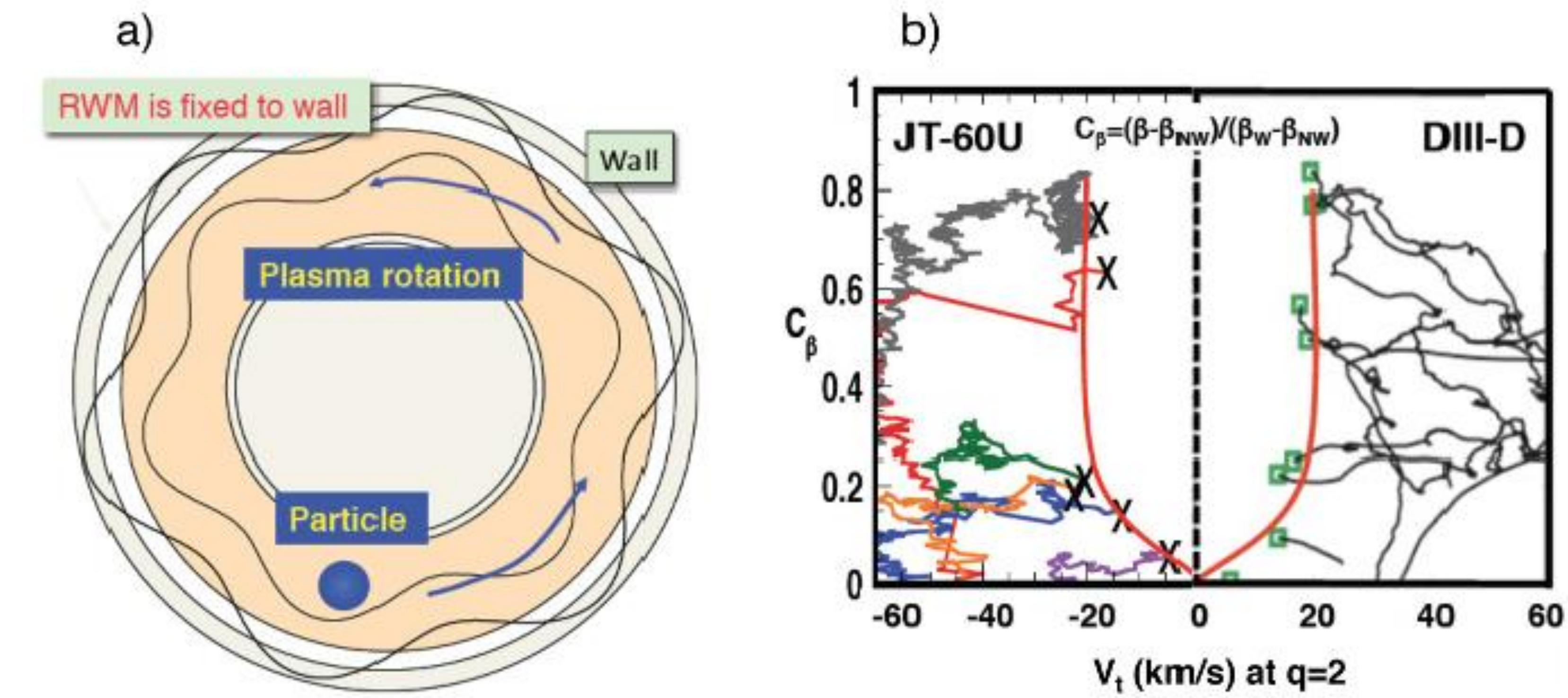
Francis Troyon (a well-known plasma physicist who discovered the scaling of plasma beta in tokamaks [46], named "Troyon scaling", without wall stabilization), he told me that he never trusted wall stabilization. As was clear from his words, the search for novel mechanisms of wall stabilization became a hot topic in advanced tokamak research from early 1990s.



Takechi PRL2007, Reimerdes PRL2007

4. Preparation to Next step - ITER

2019 10th Festival

2010

2000

1998

1990

1980

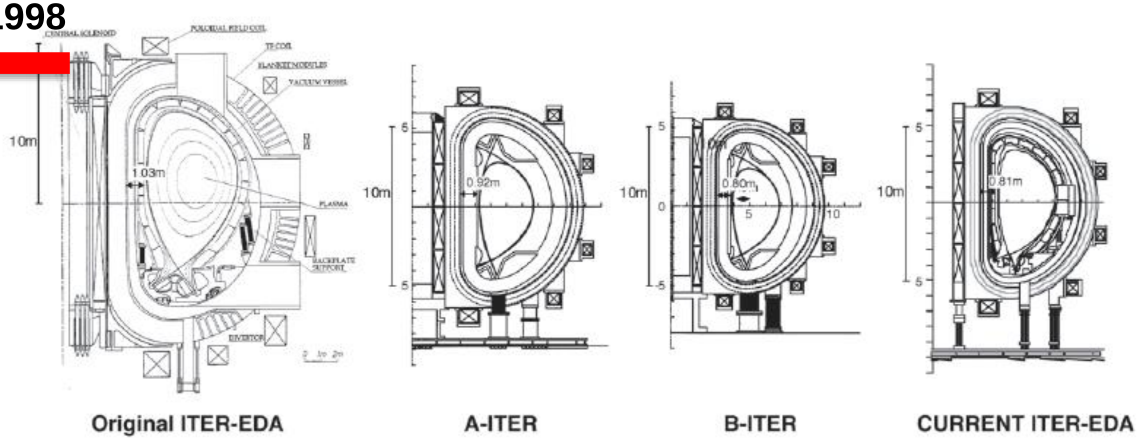
1970

1960

son for appointment to less demanding head of analysis division (1998) was diffe

-> Change Big ITER to compact ITER.

Essential role played by H. Kishimoto
For detail, see H. Kishimoto, NF2005



Later, China, Korea, India joined ITER

Rebut-Aymar-Ikeda-Motojima-Bigot

ITER SWG 1998 (Pinkau-Kishimoto chair)

4. Preparation to Next step - ITER

2019 10th Festival

US led to withdrawal from ITER (1999). US Fusion community held a workshop called the Snowmass Meeting 1999. I gave plenary talk on compact ITER is way to go.

4. Preparation to Next step - JT-60 SA

Significant budget cut of JT-60 for promoting accelerator facility at JAERI in late 1990th.
-> Modification of JT-60 to superconducting tokamak is planned from 1990.

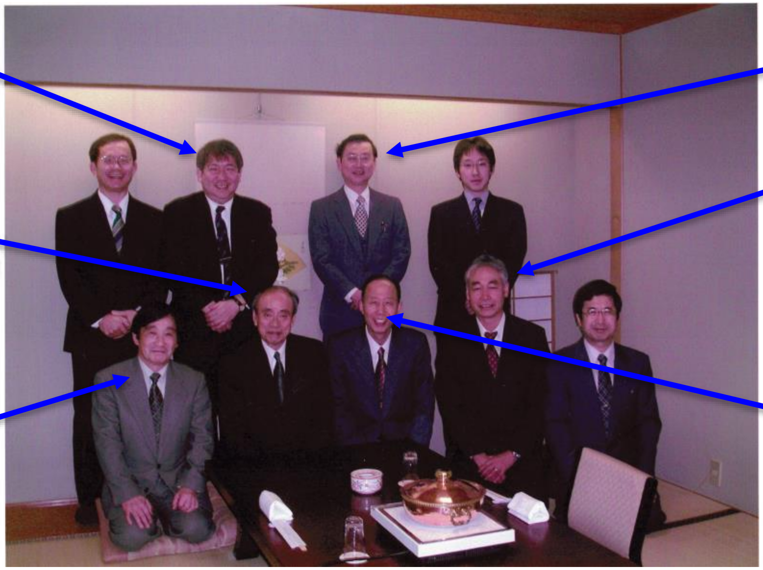
Turning point: MOE(Ministry of Education) and STA(Science and Technology Agency) merged to MEXT.

WG for fusion research (Y. Suematsu, Chair)

S. Ohtake: MEXT director for fusion

Y. Suematsu: President of Science council

N. Yoshida: Subcommittee chair for cooperation



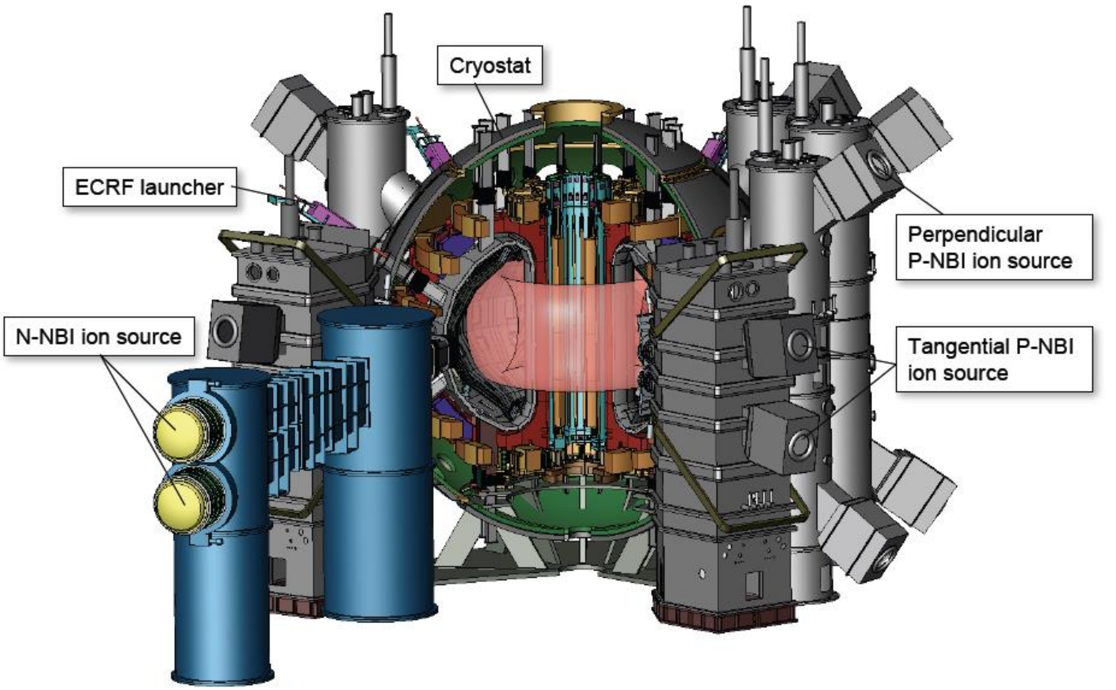
M. Kikuchi: JAERI

O. Motojima: Science advisor to MEXT

K. Yatsu: Subcommittee chair for new facility

4. Preparation to Next step - JT-60 SA

JT-60SA as satellite tokamak program under EU-Japan BA agreement



I continued to work with E.U. delegates (F. Romaneli, D. Campbell, J. Pamela and other E.U. members) to optimize the JT-60SA project specifications. While attending a workshop in Italy in September 2005, Hiro Ninomiya called to tell me that Kishimoto passed away. Less than three years later, I stepped down as Director of the JT-60 program and returned to plasma physics. In September 2015, I published a book highlighting modern tokamak physics developed during these years with M. Azumi and dedicated it to H. Kishimoto [86]. A copy was dedicated to his wife as a memory of the 10th anniversary of his death.

5. Conclusion

JT-60 operated for 23 years, from April 1985 to August 2008. Over that period, many world records in fusion performance were achieved. Numerous groups – the research staff, governmental organizations, politicians, leaders in the private sector and international partners in tokamak research – all contributed to these tremendous efforts. The large tokamak JT-60 achieved the promised parameters of JT-60 project, "density of $10^{20}/m^3$, temperature of 10^8 K, and energy confinement time of 1 s", simultaneously. The JT-60 experiments motivated me to reconstruct the fusion reactor concept. The research direction of JT-60 was also redirected to this new concept. While fusion physics and technology made outstanding progress through JT-60 experiments, the road to fusion energy still has many challenges. Creation of the first plasma was just the beginning of fusion energy experiments. This will be true for ITER and enormous effort will be necessary to advance fusion science and solve many issues to realize an economically viable fusion system. I share the opinion of E. Teller that this effort is highly rewarding.