2010 IISS at IFS, Texas University, May31-June 4

Physics of Plasma control Towards Steady-state Operation of ITER

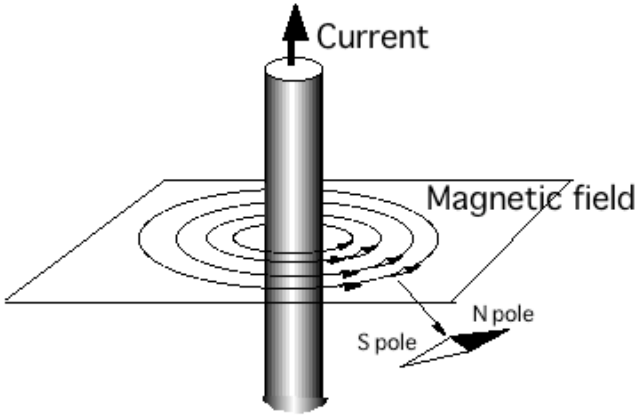
M. Kikuchi, JAEA
D.J. Campbell, ITER Organization

Outline of talk

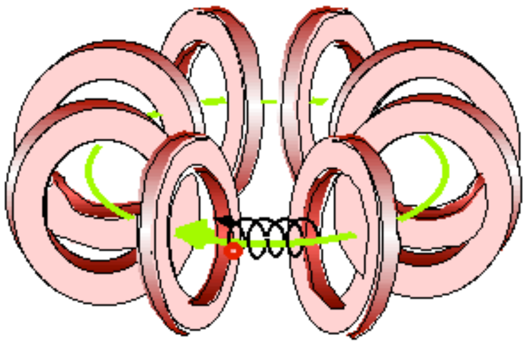
- **Fusion research**
- **ITER and its Actuator**
- **Physics elements towards steady state operation of ITER**

0. What is Tokamak : Topology is torus. It has Geometrical Symmetry

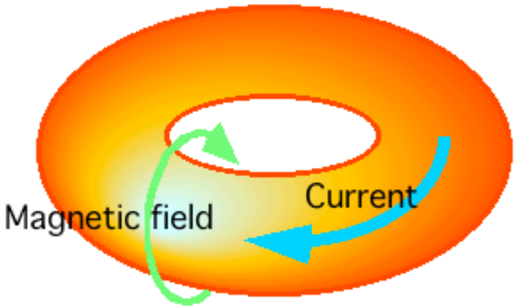
i) Magnetic field around the current



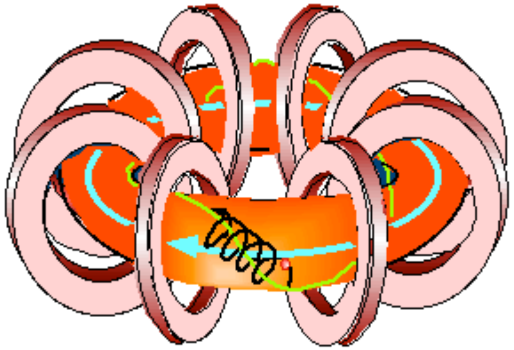
ii) Magnetic field by cylindrical curcular coils

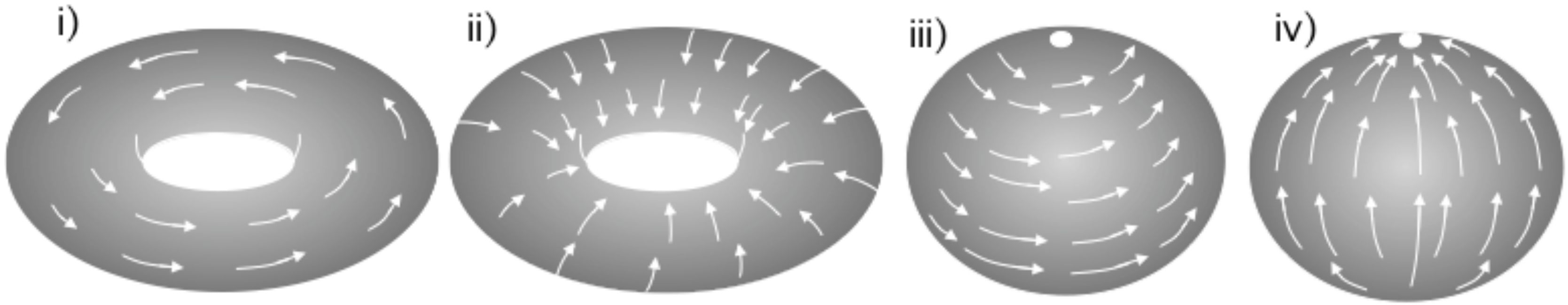


iii) Magnetic field by toroidal current



iv) Twisted field line by b)and c)

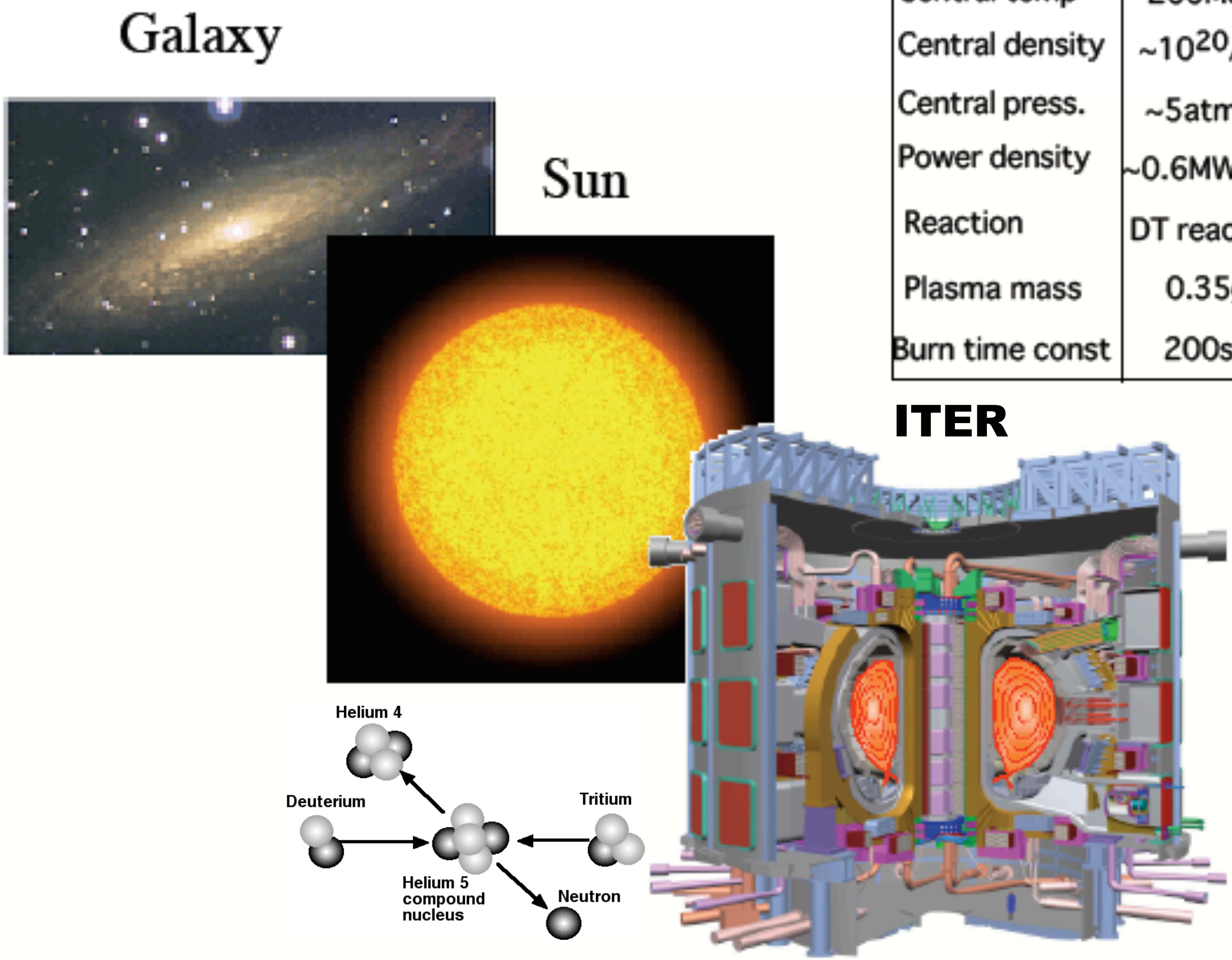


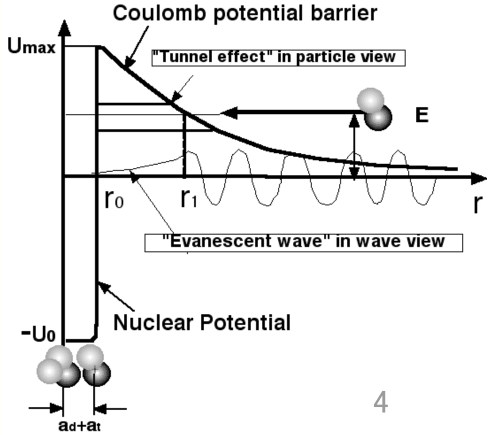


1. ITER is first trial to bring the Sun on the Earth

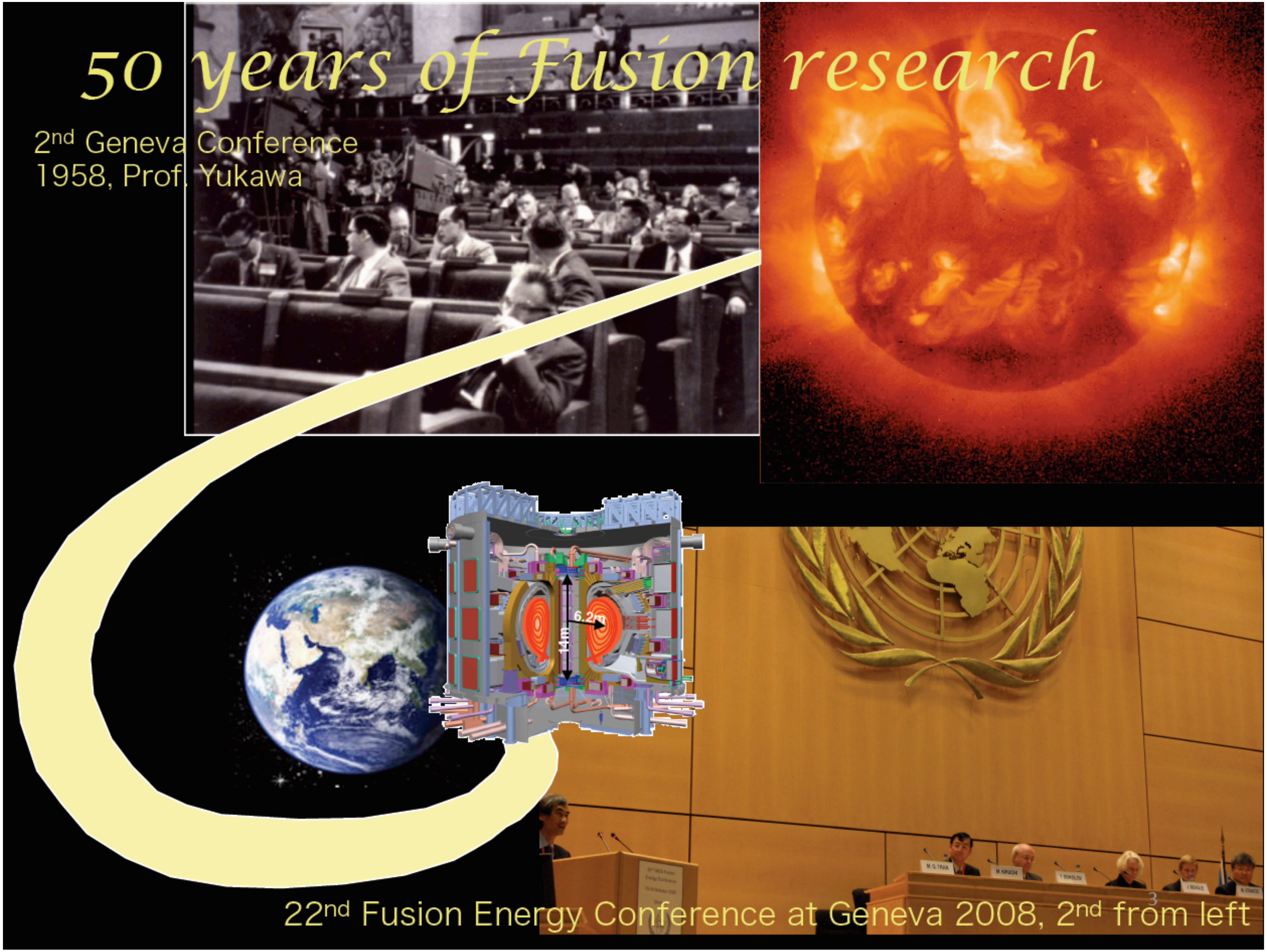
Mission : ITER have to show scientific and technological feasibility of fusion energy.

Quantity	ITER	Sun	Ratio
Diameter	16.4m	140×10^4km	~$1/10^8$
Central temp	200Mdeg	15Mdeg	10
Central density	~$10^{20}/m^3$	~$10^{32}/m^3$	10^{12}
Central press.	~5atm	~10^{12}atm	~10^{11}
Power density	~$0.6MW/m^3$	~$0.3W/m^3$	~2×10^6
Reaction	DT reaction	pp reaction	
Plasma mass	0.35g	2×10^{30}kg	$1/6\times10^{33}$
Burn time const	200s	10^{10}years	10^{15}





50 years of Fusion research

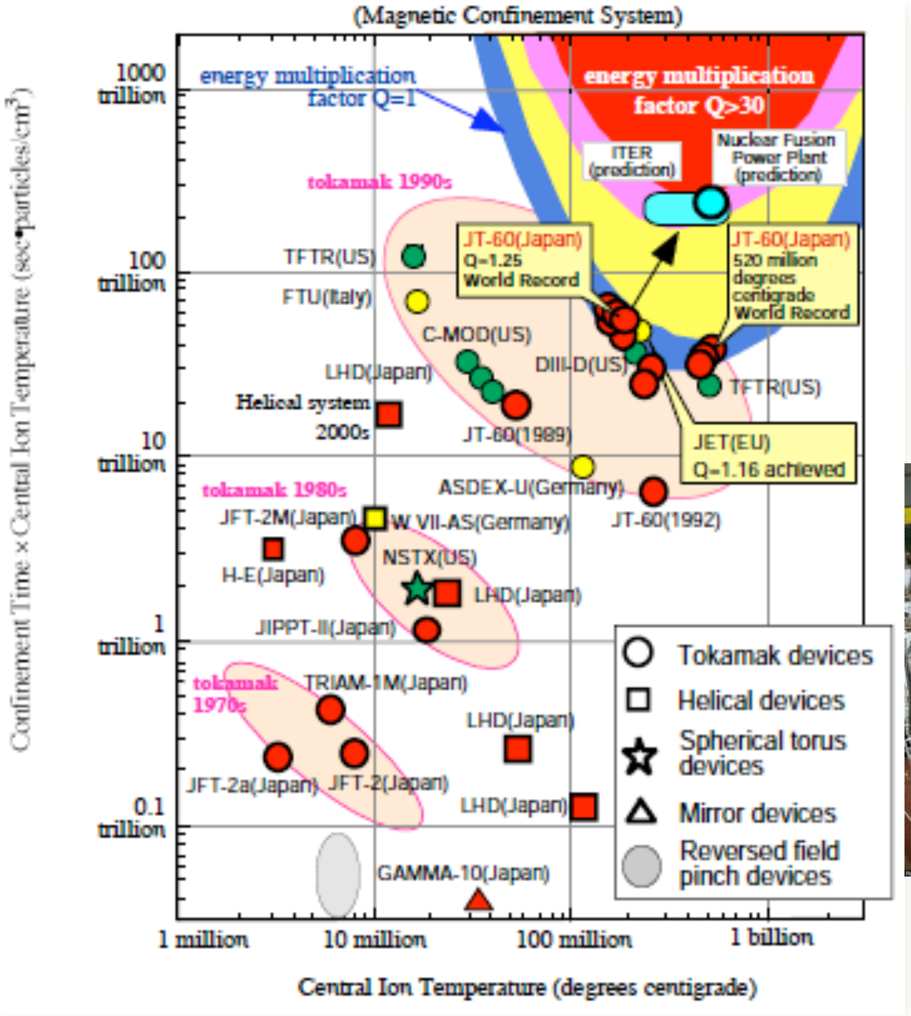


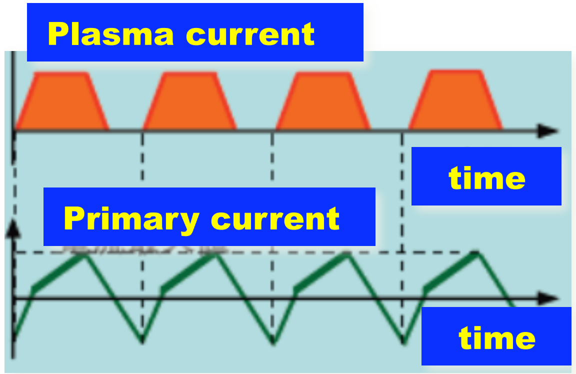
2nd Geneva Conference
1958, Prof. Yukawa

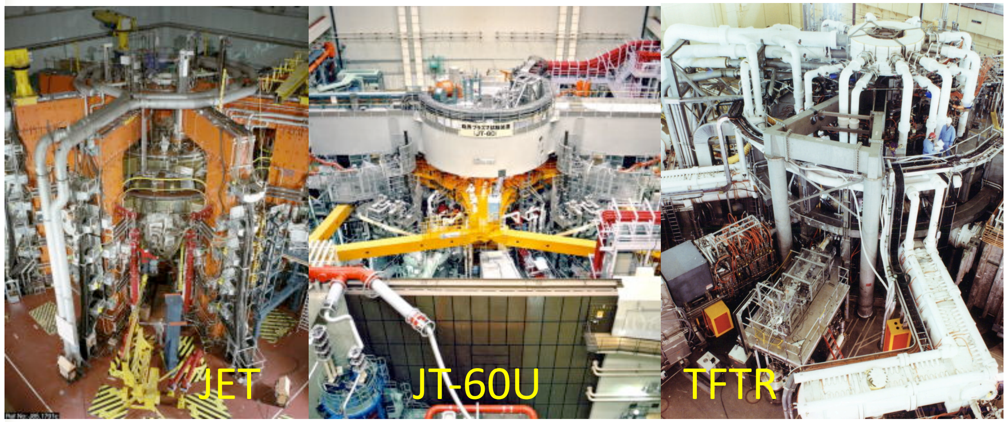
22nd Fusion Energy Conference at Geneva 2008, 2nd from left

6. Tokamak made great advances but has drawback.

Tokamak shows good confinement but is not intrinsically steady-state.
Continuous fusion power from DEMO is much more preferable.
ITER will challenge steady-state operation of tokamak system.







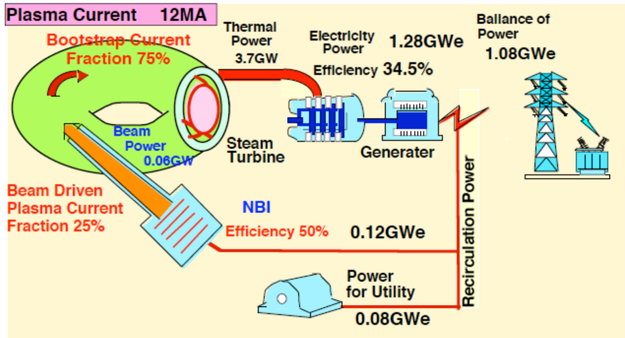
3 Large Tokamaks, DIII-D and other tokamaks provided basis for ITER

7. Steady state tokamak reactor as DEMO and commercial

To resolve pulsed nature of Tokamak system,
use of bootstrap current and active current drive is essential.

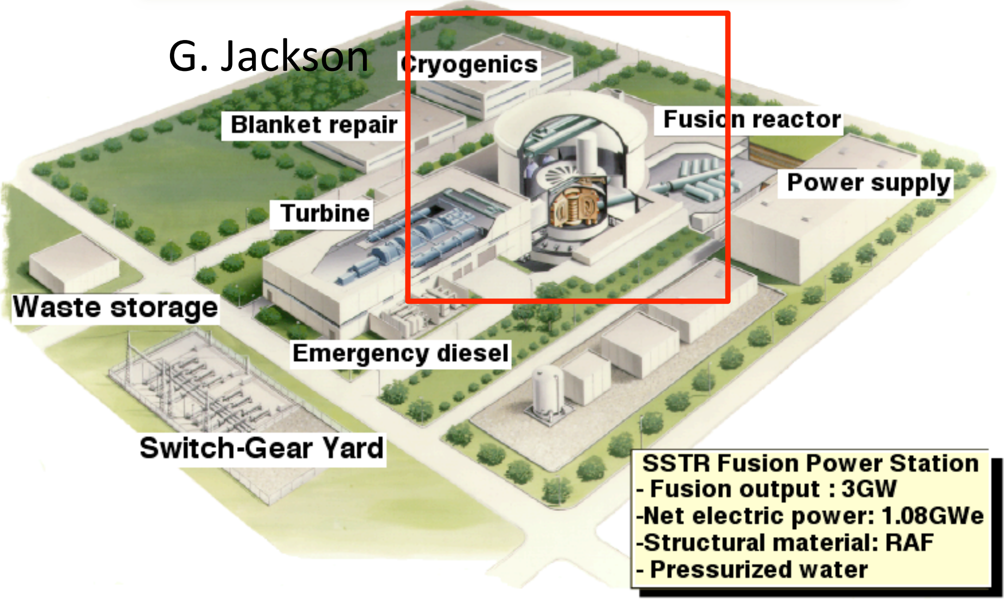
Principle of SSTR

A low Ip with a large Bootstrap Current fraction allows reduction of re-circulation power.

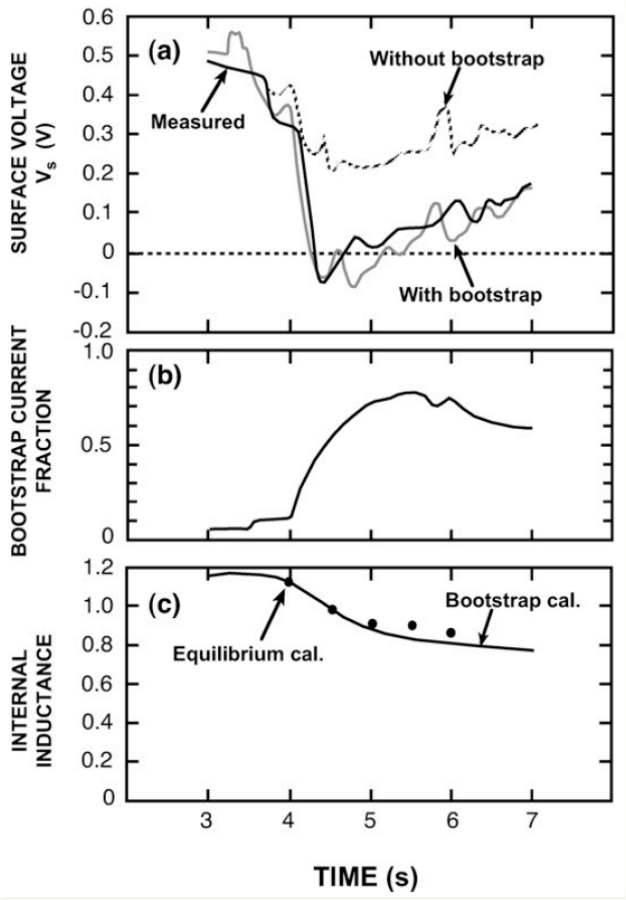


80% bootstrap fraction in JT-60 is a basis for this concept

G. Jackson



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



M. Kikuchi, M. Azumi, PPCF 37(1995)1215

ITER and its Actuator

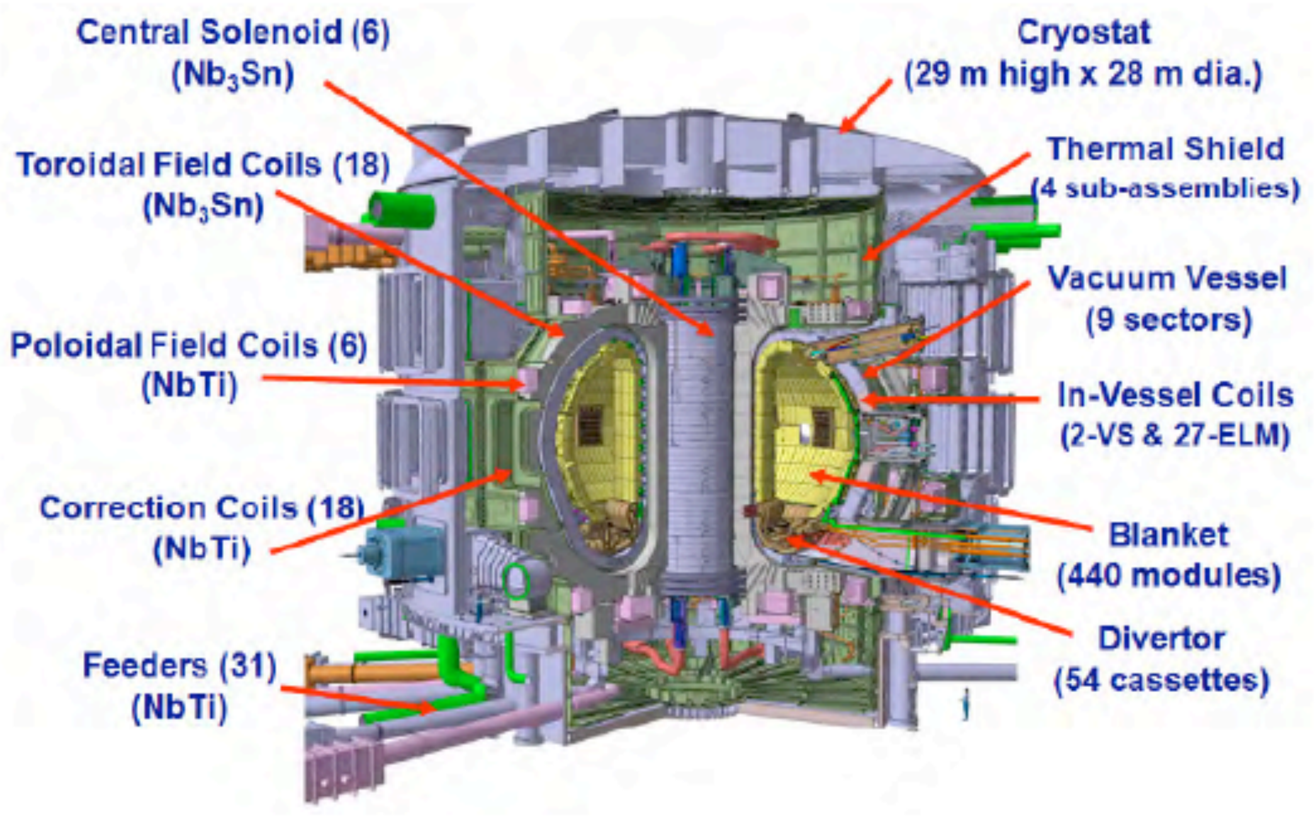
(see details by J. Snipes, next talk)

1. ITER

The principal physics goals of ITER

1) Achieve extended burn in inductively-driven plasmas with Q of at least 10 for a range of operating conditions, and of duration sufficient to achieve stationary conditions on the time scales characteristic of plasma processes.

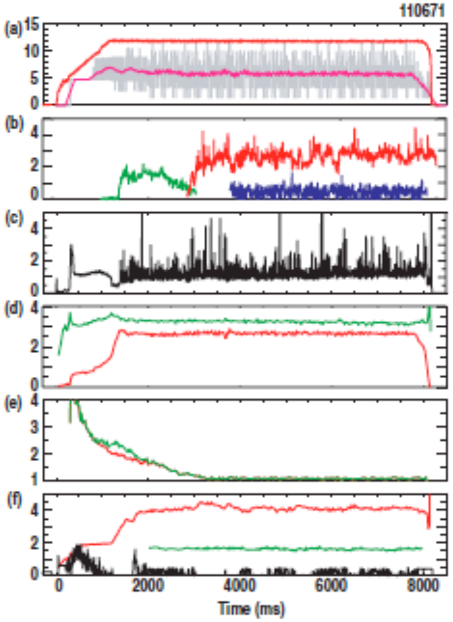
2) Aim at demonstrating steady-state operation using non-inductive current drive with a ratio of fusion power to input power of at least 5.

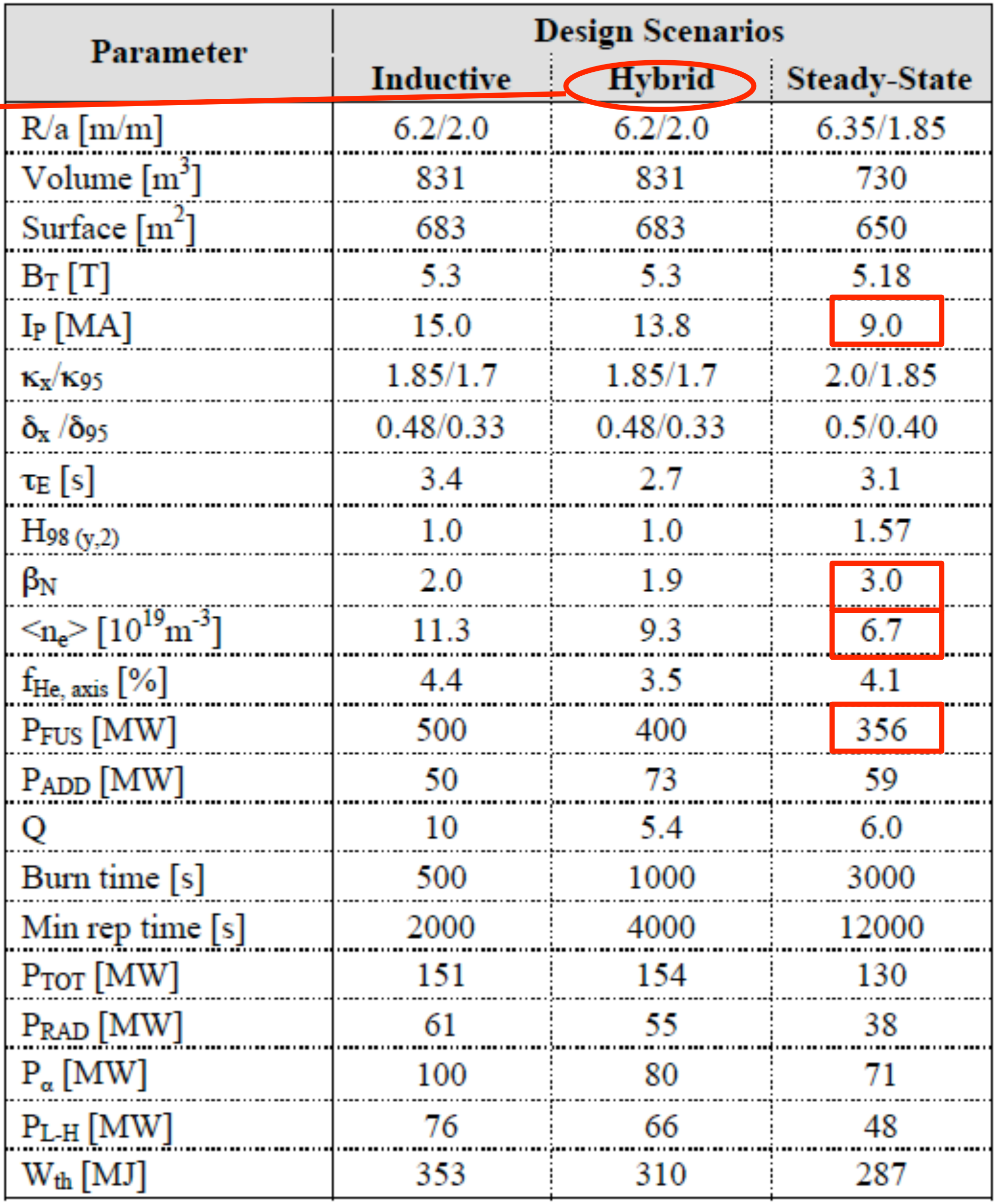


Plasma current	15MA
Toroidal field	5.3T
Major radius	6.2m
Minor radius	2.0m
Elongation κ_x/κ_{95}	1.85/1.7
Triangularity δ_x/δ_{95}	0.48/0.33
Fusion power	500MW
Q	10
Burn time	~400s

2. ITER Operation Scenarios

Nuclear Fusion Prize 2006
For Hybrid (T. Luce)





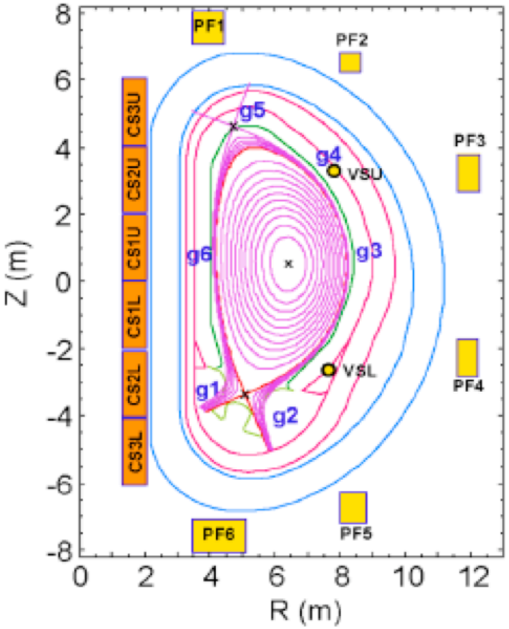
Parameter	Design Scenarios		
	Inductive	Hybrid	Steady-State
R/a [m/m]	6.2/2.0	6.2/2.0	6.35/1.85
Volume [m^3]	831	831	730
Surface [m^2]	683	683	650
B_T [T]	5.3	5.3	5.18
I_P [MA]	15.0	13.8	9.0
κ_x/κ_{95}	1.85/1.7	1.85/1.7	2.0/1.85
δ_x/δ_{95}	0.48/0.33	0.48/0.33	0.5/0.40
τ_E [s]	3.4	2.7	3.1
$H_{98\,(y,2)}$	1.0	1.0	1.57
β_N	2.0	1.9	3.0
$<n_e>$ [$10^{19}m^{-3}$]	11.3	9.3	6.7
$f_{He,\,axis}$ [%]	4.4	3.5	4.1
P_{FUS} [MW]	500	400	356
P_{ADD} [MW]	50	73	59
Q	10	5.4	6.0
Burn time [s]	500	1000	3000
Min rep time [s]	2000	4000	12000
P_{TOT} [MW]	151	154	130
P_{RAD} [MW]	61	55	38
P_α [MW]	100	80	71
P_{L-H} [MW]	76	66	48
W_{th} [MJ]	353	310	287

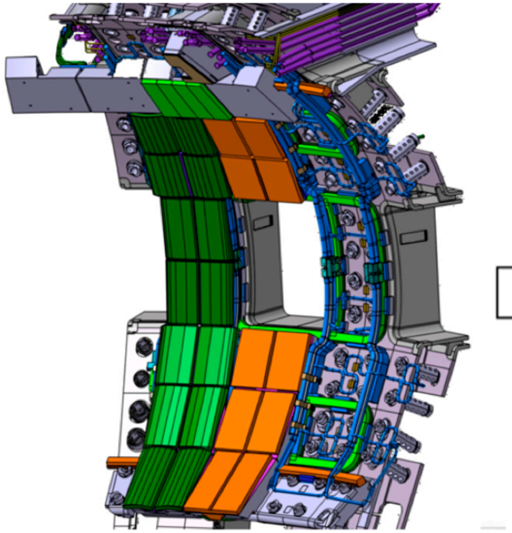
Not yet for
Steady-state

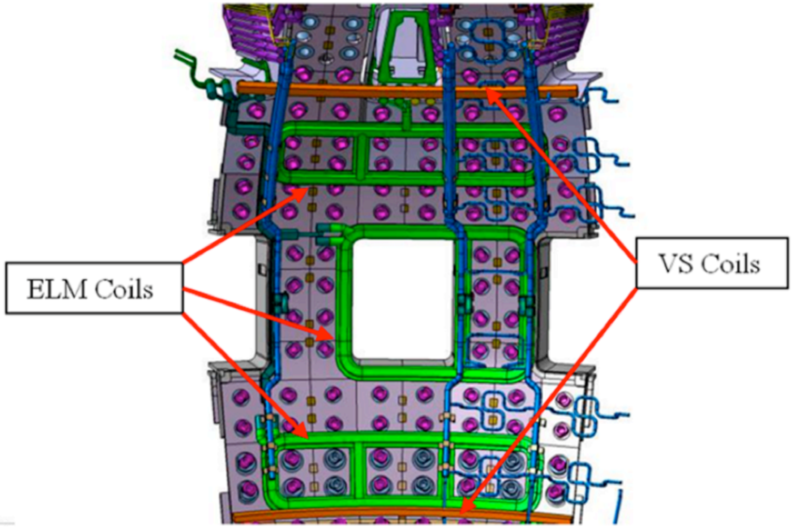
2. ITER Actuators (1) Magnetic field control tools

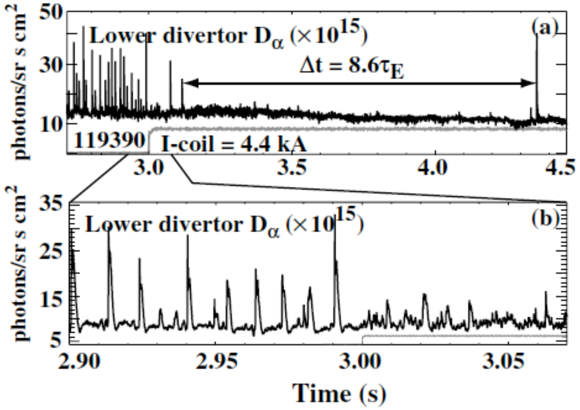
Shape, Position Control : PF1-PF6 (SC)
Fast vertical feedback control: VS coils (NC)
Plasma current control : CS1-CS6 (SC)

ELM control : ELM coils
RWM control : use ELM coils

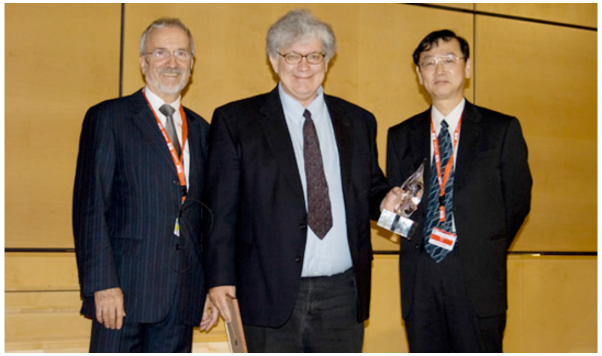






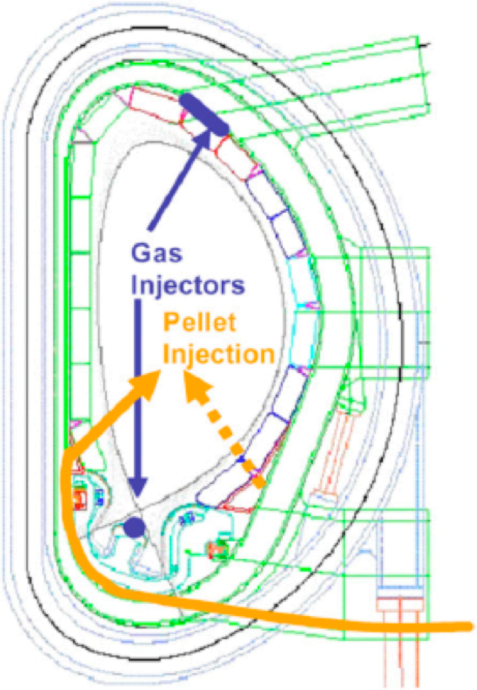


2008 Nuclear Fusion Prize for ELM suppression



T. Evans

3. ITER Actuators (2) Pellet &Divertor pumping



Baylor : NF 2007

High field side Pellet Injector : Core fuelling

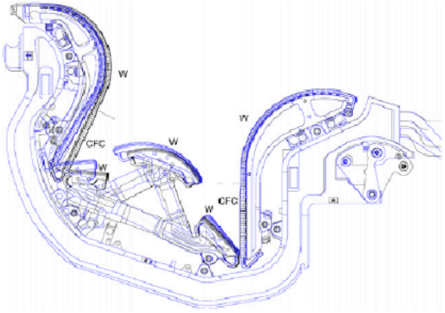
: Density peaking

Low field side Pellet Injector : ELM pacing

P T Lang et al: ELM pace making and mitigation by pellet injection in ASDEX Upgrade : one of 2007 NFP 10 nominees

Density peaking has strong influence on fusion performance. When ITG plays dominant role in transport, density will be peaked while it will flatten if TEM play major role as shown by Angioni NF2004.

2007 Nuclear Fusion Prize for physics of density peaking



Kukushkin: NF2009

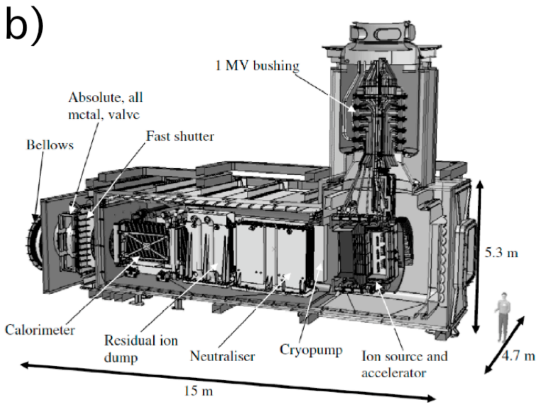
C. Angioni

4. ITER Actuators (3) H&CD system

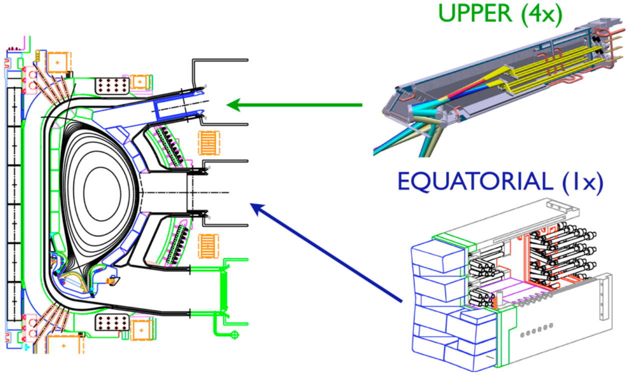
Heating NB system
-1MeV, 16.5MWx2
-3600s
-On and off CD by tilting capablity Δz

EC system
-170MHz, 20MW
- Upper 4 for localized H&CD (r>mid r) (NTM, sawtooth) 1kHz modulation
-Equatorial for broader H&CD (r<mid r)
Startup assist, Central H&CD

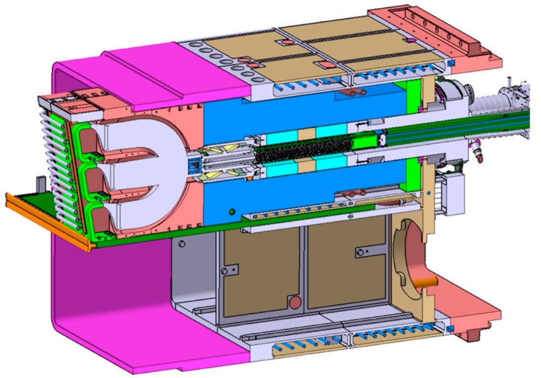
IC system
-~50MHz, 20MW
T 2^{nd} Harmonic resonance



Hemsworth NF2009



Henderson 2006



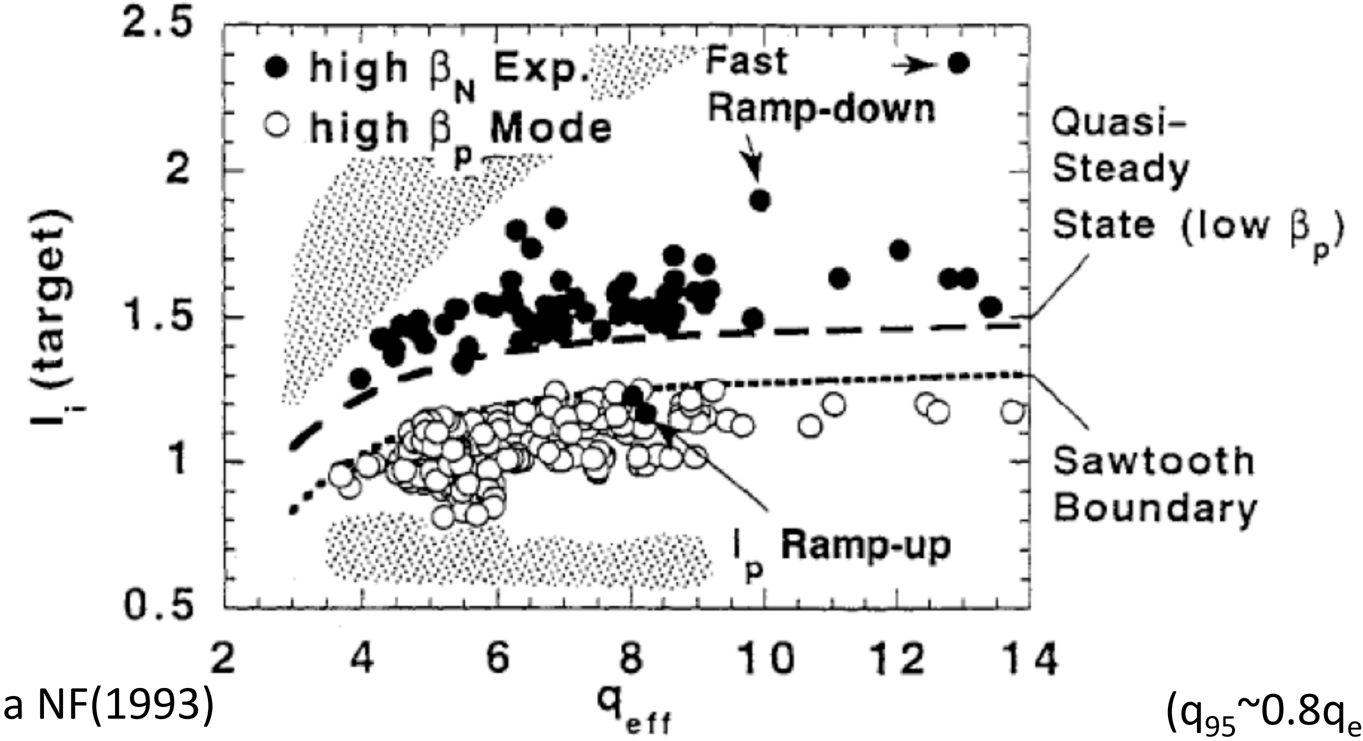
Milanesio NF2010

Plasma Operating Regime toward Steady-state Operation of tokamak

1. Cheng's (q,li) diagram

F. Cheng, Furth, Boozer (1987) analyzed MHD stability of tokamak to propose (q,li) diagram for tokamak operating space. J. Snipes NF(1988) for non-circular plasma (JET). Steady state tokamak may need operating in low li since bootstrap current is hollow.

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\psi}{dr}\right)-\frac{m^2}{r^2}\psi-\frac{\mu_0 dJ/dr}{B_\theta(1-nq/m)}\psi=0$$



Kamada NF(1993)

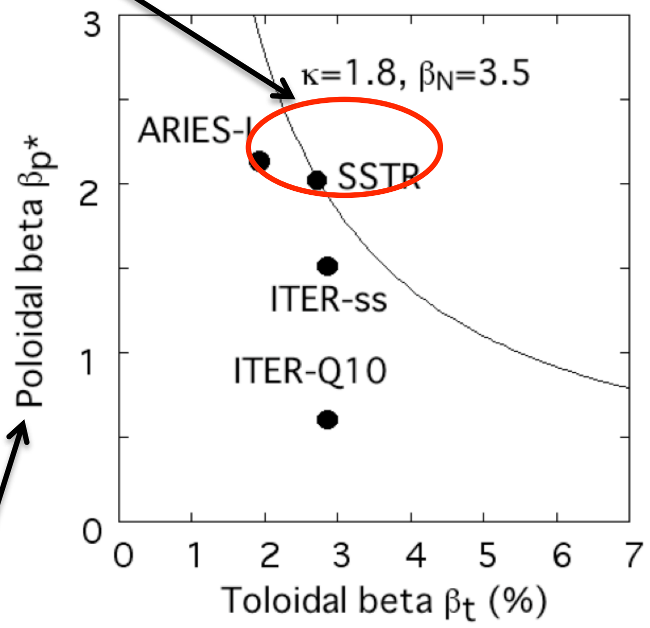
(q_{95}~$0.8q_{eff}$)

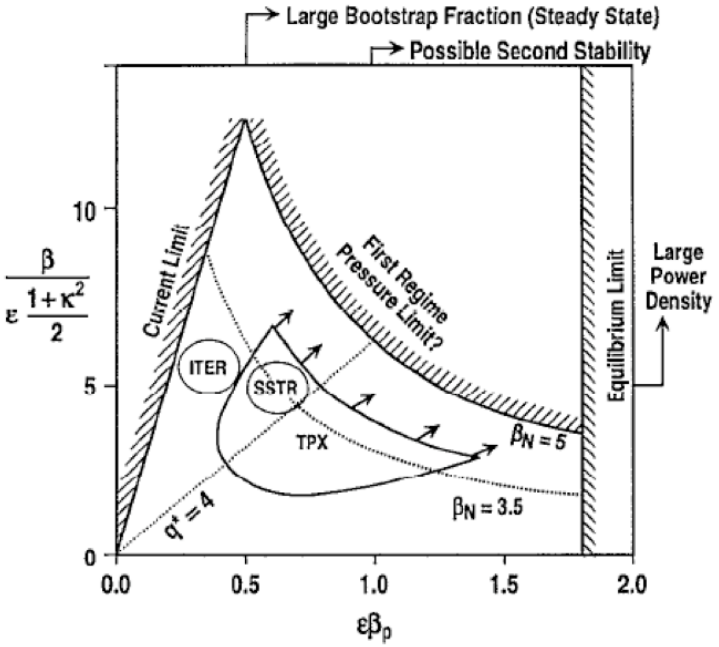
2. (β_t, β_p) diagram

F. Troyon (1984) derived most famous scaling for ideal MHD stability of tokamak called Troton scaling $\beta_t=\beta_N I_p/aB_t$, which leads to relation with poloidal beta $\beta_{p*}=(4/(\mu_0 I_p^2 R_p))\int PdV$.

$$\beta_{p*}\beta_t = \frac{\kappa}{4}\beta_N^2$$

Steady state tokamak reactor regime





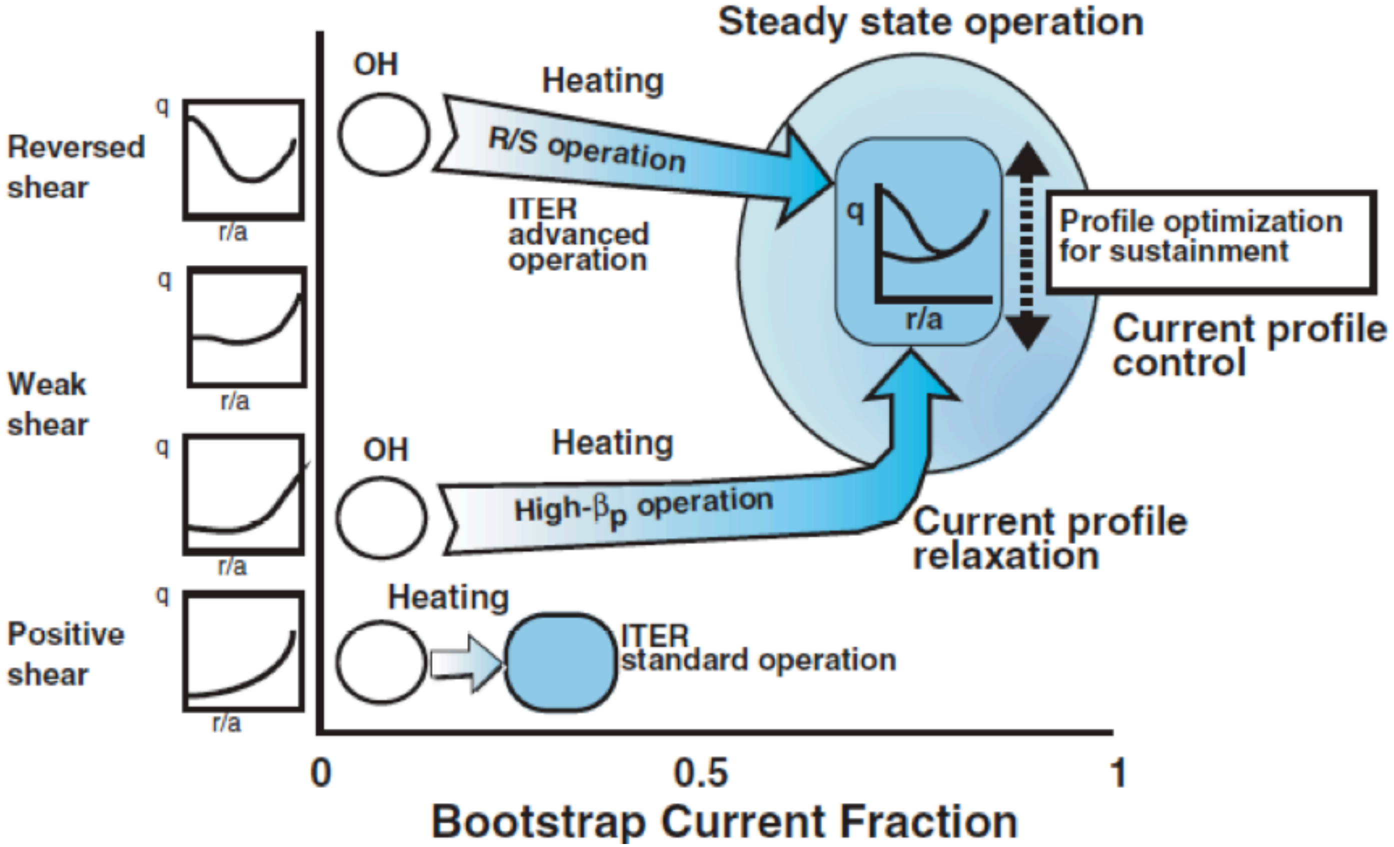
Proportional to bootstrap current fraction

M. Kikuchi, NF (1990)

T. Taylor PPCF(1997)

3. Advanced tokamak operation : profile control

Current profile control is important for obtaining high performance plasma in ITER and also essential for steady state operation of tokamaks.



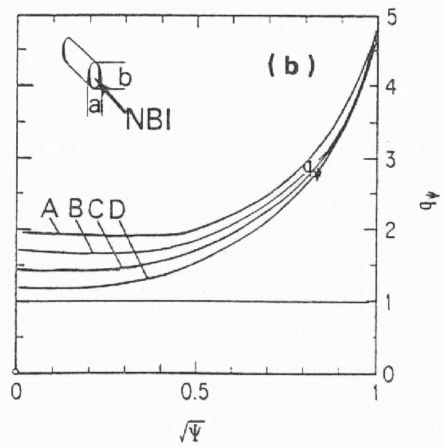
H. Kishimoto, S. Ishida, M. Kikuchi, N. Ninomiya NF(2005)

See details Litaudon (Tuesday morning)

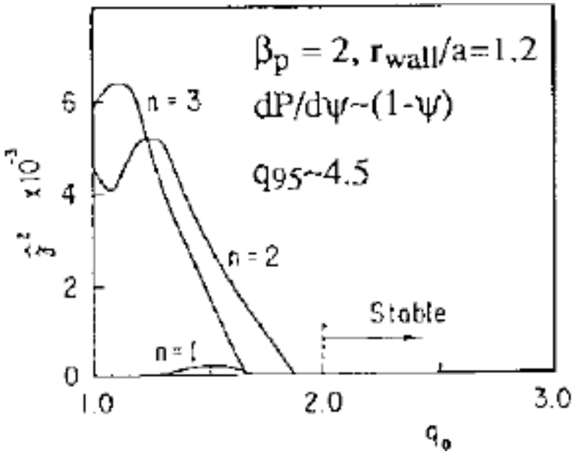
4. Weak shear regime :

Originally proposed for SSTR (Kikuchi, (1990)) :
-High q(0) with wall stabilization gives stable plasma at high βp.
-Improved confinement without sawtooth

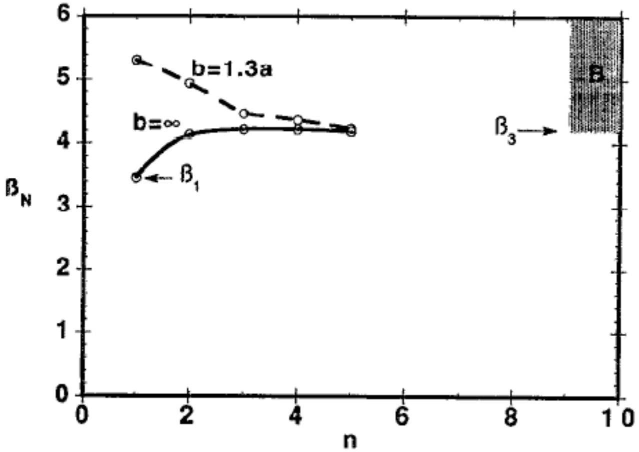
-Issue : Wall stabilization. -> see RWM later
-Issue : loss of wall stabilization /not extreme. (see Manickham (1994)
-Issue : Edge bootstrap current excites MHD modes
-Issue : NTM in positive shear -> see NTM later



Kikuchi NF (1990)



Kikuchi PPCF (1993)



Manickham PoP (1994)

5. Negative shear regime:

T. Ozeki (1992) ; first proposal to use NS for steady state operation of tokamak.

Point :

-Reduce pressure gradient near q_{min} -> Not consistent with large J at q_{min}

-Supplement off-axis NB near q_{min}

Issue :

-Loss of wall stabilization has big effect. (Manicham (1994)

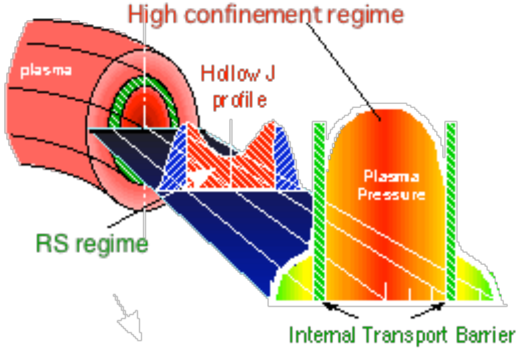
Nonetheless Murakami NF(2005) achieved

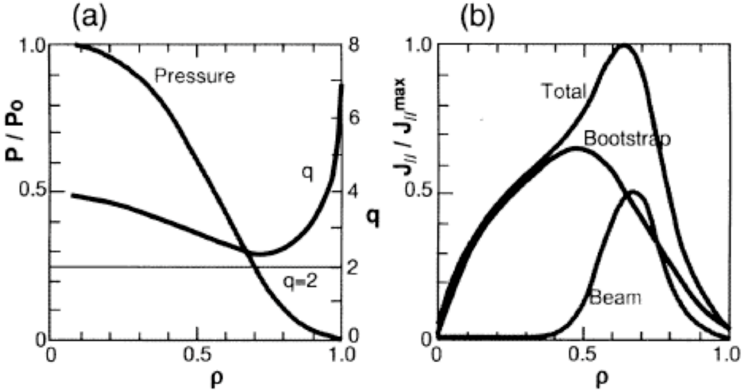
$$q_{95}=5,\ \beta_N=3.5,\ \beta_t=3.6\%,\ H_{89}=2.4$$

Issue :

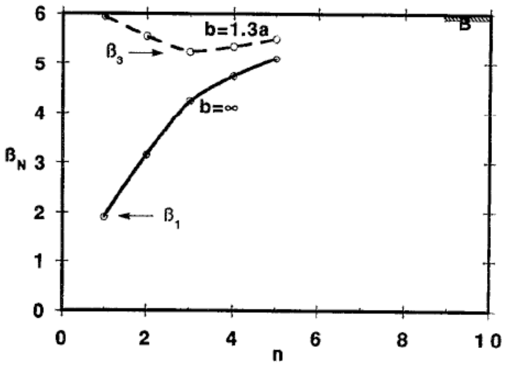
-edge bootstrap current

- n=1 mode to terminate discharges

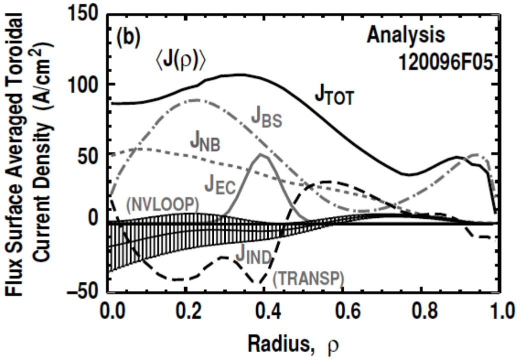




T. Ozeki (1992)



Manicham PoP (1994)



Murakami NF(2005)

6. Current Hole regime:

T. Fujita and N.C. Hawkes (2001) found stable current hole in the center of NS plasmas.

Good point :

-Have lower li and easier to get more elongated plasma.

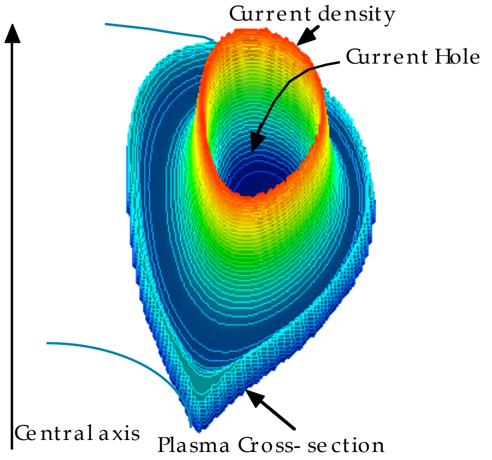
-Easier to get higher bootstrap current fraction

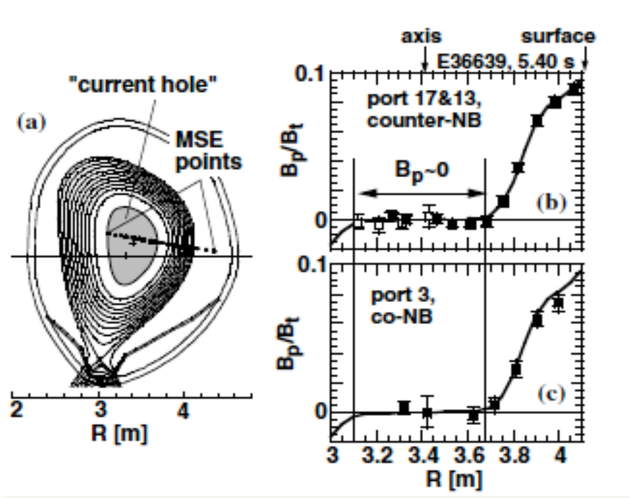
Issue :

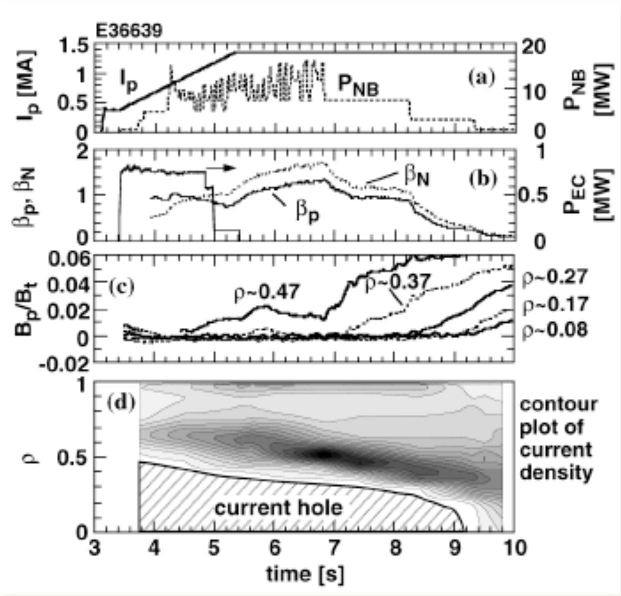
-Ripple loss may be enhanced , severe ripple constraint.

-Lower β limit without wall stabilization

T. Fujita et al., P.R.L. 87(2001)245001
N.C. Hawkes et al., P.R.L. 87(2001)115001







Physics Elements of Plasma control towards steady-state operation of ITER

1. Generalized Ohm's Law

Hirshman-Sigmar moment equation for momentum and heat flow

$$\underbrace{\begin{bmatrix} \mu_{a1} & \mu_{a2} \\ \mu_{a2} & \mu_{a3} \end{bmatrix} \begin{bmatrix} \langle Bu_{//a} \rangle - BV_{1a} \\ \langle 2Bq_{//a}/5P_a \rangle - BV_{2a} \end{bmatrix}}_{\text{Viscous force}} = \underbrace{\sum_b \begin{bmatrix} l_{11}^{ab} & -l_{12}^{ab} \\ -l_{21}^{ab} & l_{22}^{ab} \end{bmatrix} \begin{bmatrix} \langle Bu_{//b} \rangle \\ \langle 2Bq_{//b}/5P_b \rangle \end{bmatrix}}_{\text{Friction force}} + \begin{bmatrix} e_a n_a \langle BE_{//} \rangle \\ 0 \end{bmatrix} + \begin{bmatrix} \langle BM_{a//} \rangle \\ \langle BQ_{a//} \rangle \end{bmatrix}$$

Viscosity matrix →

$$\mathbf{M}(\mathbf{U}_{//} - \mathbf{V}_{\perp}) = \mathbf{L}\mathbf{U}_{//} + \mathbf{E}^{*} + \mathbf{S}_{//}$$

Parallel flows

Thermodynamic forces

Friction matrix

$$\langle \mathbf{B} \cdot \mathbf{J} \rangle = \langle \mathbf{B} \cdot \mathbf{J} \rangle_{bs} + \sigma_{//}^{NC} \langle \mathbf{B} \cdot \mathbf{E} \rangle + \underbrace{\langle \mathbf{B} \cdot \mathbf{J} \rangle_{NBCD} + \langle \mathbf{B} \cdot \mathbf{J} \rangle_{RFCD}}_{\text{Non-inductive CD}}$$

Bootstrap current

Neoclassical conductivity

$$\sigma_{//}^{NC} \langle \mathbf{B} \cdot \mathbf{E} \rangle = \sum_{a=e,i,I} e_a n_a \left\{ \sum_{b=1}^{3} \left[(\mathbf{M} - \mathbf{L})^{-1} \right]_{ab} e_b n_b \langle BE_{//} \rangle \right\}$$

$$\langle \mathbf{B} \cdot \mathbf{J} \rangle_{bs} = \sum_{a=e,i,I} e_a n_a \left\{ \sum_{b=1}^{6} \left[(\mathbf{M} - \mathbf{L})^{-1} \mathbf{M} \right]_{ab} V_{\perp b} \right\}$$

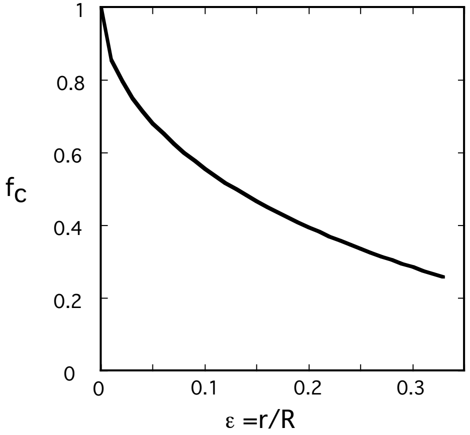
$$\langle \mathbf{B} \cdot \mathbf{J} \rangle_{NBCD} + \langle \mathbf{B} \cdot \mathbf{J} \rangle_{RFCD} = \sum_a e_a n_a \left\{ \sum_b \left[(\mathbf{M} - \mathbf{L})^{-1} \right]_{ab} S_{// b} \right\}$$

2. Conduction Current : Neoclassical conductivity

$$\sigma_{//}^{NC} = \sum_{a=e,i,I}\sum_{b=e,i,I} e_a n_a e_b n_b \left[(\mathbf{M}-\mathbf{L})^{-1}\right]_{ab}$$

$$\sigma_{//}^{sp} = -\sum_{a=e,i,I}\sum_{b=e,i,I} e_a n_a e_b n_b \mathbf{L}^{-1}{}_{ab}$$

Circulating particle fraction



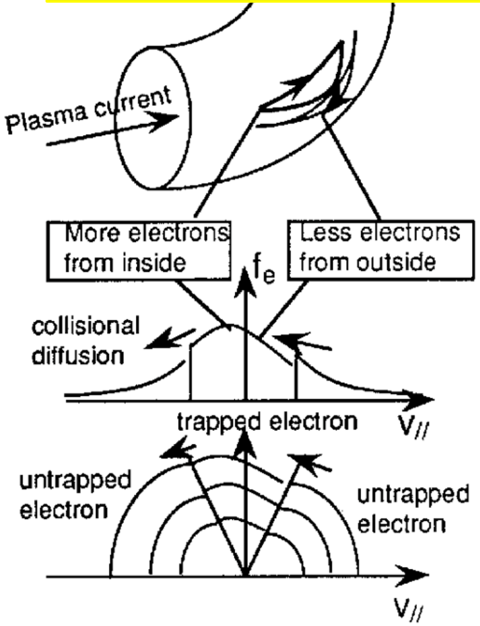
$$\sigma_{//}^{NC} = \sigma_{//}^{Spitzer}\left[1-\frac{f_t}{1+\xi\nu_e^*}\right]\left[1-\frac{C_R f_t}{1+\xi\nu_e^*}\right]$$

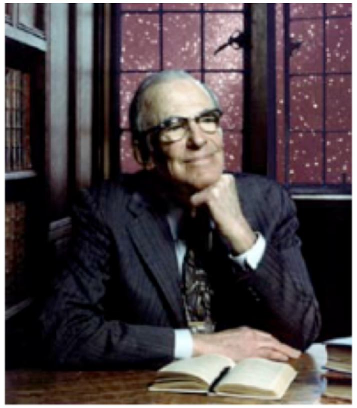
$$C_R(Z_{eff}) = \frac{0.56}{Z_{eff}}\frac{3-Z_{eff}}{3+Z_{eff}}, \xi(Z_{eff}) = 0.58 + 0.2Z_{eff}$$

$$f_t = 1 - \frac{(1-\varepsilon)^2}{(1+1.46\varepsilon^{1/2})\sqrt{1-\varepsilon^2}}$$

Hirshman, Hawryluk, Birge NF(1977)

Origin of viscous force





L. Spitzer Jr. first derived electrical conductivity in fully ionized plasma.

3. Bootstrap Current

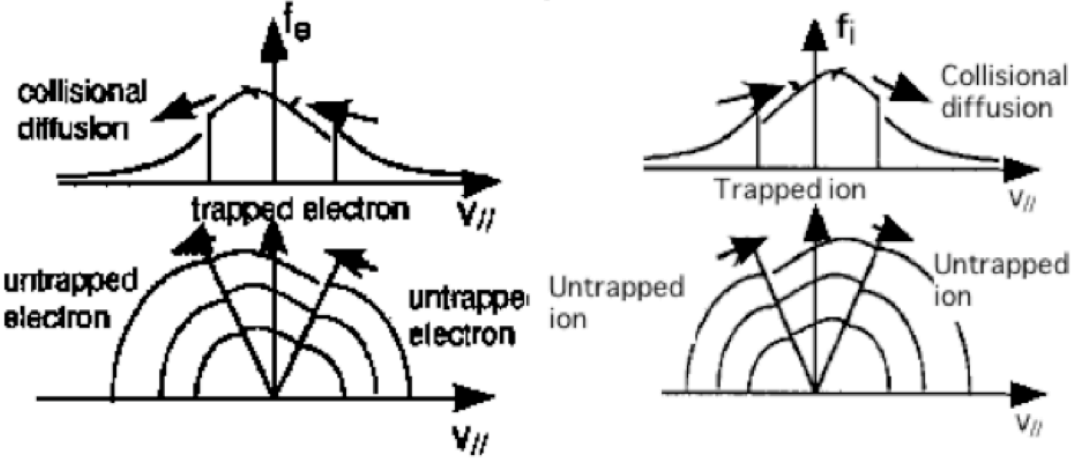
$$\langle \mathbf{B}\cdot\mathbf{J}\rangle_{bs} = \sum_{a=e,i,I} e_a n_a \sum_{b=1}^{6} \alpha_{ab} V_{\perp b}$$

$\boldsymbol{\alpha}$**=(M-L)**$^{-1}$**M**

$$\langle \mathbf{B}\cdot\mathbf{J}\rangle_{bs} = -F(\psi) n_e(\psi) \sum_{a=e,i,I} \frac{1}{|Z_a|}\left[L^a_{31} \frac{1}{n_a(\psi)} \frac{dP_a(\psi)}{d\psi} + L^a_{32} \frac{dT_a(\psi)}{d\psi} \right]$$

$$L^a_{31} = \sum_{b=e,i,I} \frac{|Z_a|}{Z_a} \frac{Z_b n_b}{n_e} \alpha_{ab} \qquad L^a_{32} = \sum_{b=e,i,I} \frac{|Z_a|}{Z_a} \frac{Z_b n_b}{n_e} \alpha_{a,b+3}$$

Origin of bootstrap current



R. Bickerton was first noted importance of bootstrap current for steady state operation of tokamak

4. Beam-driven Current

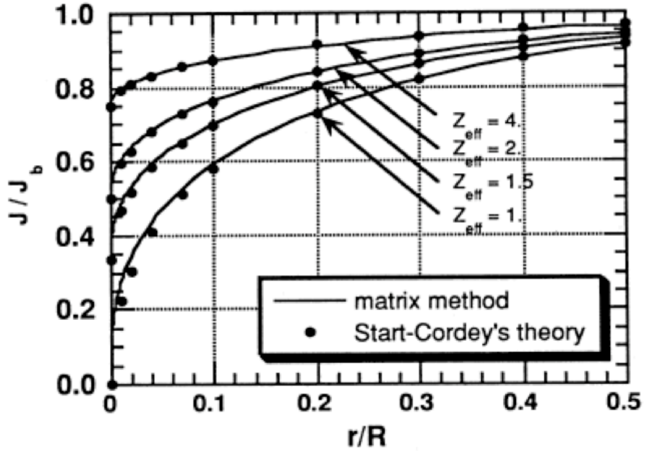
$$\left\langle \vec{J}_{bd} \cdot \vec{B} \right\rangle = \sum_{a=e,i,I,b} e_a n_a \left\langle \hat{u}_a \cdot \vec{B} \right\rangle = \sum_{a=e,i,I,b} e_a n_a (\hat{M} - \hat{L})^{-1}{}_{ab} S_b$$

$$\left\langle \vec{J}_{fast} \cdot \vec{B} \right\rangle = e_b n_b (\hat{M} - \hat{L})^{-1}{}_{bb} S_b$$

$$\left\langle \vec{J}_{shield} \cdot \vec{B} \right\rangle = \sum_{a=e,i,I} e_a n_a (\hat{M} - \hat{L})^{-1}{}_{ab} S_b$$

Stacking factor

$$F = \sum_{a=e,i,I,b} e_a n_a (\hat{M} - \hat{L})^{-1}{}_{ab} / e_b n_b (\hat{M} - \hat{L})^{-1}{}_{bb}$$



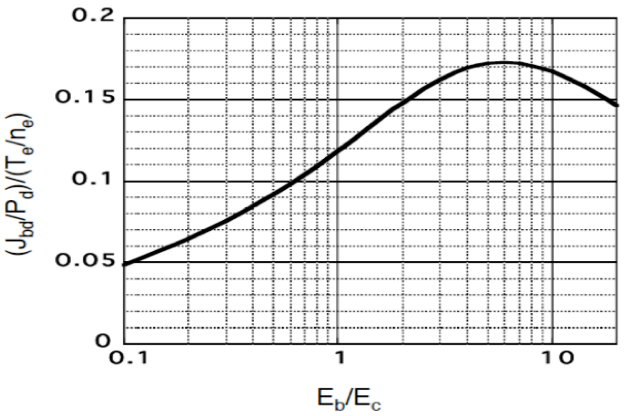
Wesson crude estimates

$$J_{fast} = \frac{S\tau_{se} Z_b v_{b0}}{1 + E_c / E_{b0}} \int_0^1 f_1 u^3 du = \frac{S\tau_{se} Z_b v_{b0}}{1 + E_c / E_{b0}} \int_0^1 u^{2\beta} \left[\frac{1 + (E_c / E_{b0})^{3/2}}{u^3 + (E_c / E_{b0})^{3/2}}\right]^{1+2\beta/3} u^3 du$$

$$\frac{J_{bd}}{P_d} \sim \frac{2\tau_{se} e Z_b F}{m_b v_{b0} (1 + E_c / E_{b0})} \int_0^1 f_1 u^3 du$$

$$\eta_{CD} \equiv \frac{I_{CD} \bar{n}_e R}{P_{CD}} = \frac{\bar{n}_e R \int J_{bd} dS}{\int P_{cd} dV} \propto \langle T_e \rangle \eta(E_b / \langle E_c \rangle)$$

$$\eta(E_{b0} / E_c) = \frac{1}{1 + E_c / E_{b0}} \int_0^1 \left[\frac{1 + (E_c / E_{b0})^{3/2}}{u^3 + (E_c / E_{b0})^3}\right]^{1+2\beta/3} u^{2\beta+3} du$$



5. Toroidal Rotation in Tokamak

Summation of momentum balance equation

$$\sum_a m_a n_a \frac{du_a}{dt} = \mathbf{J}\times\mathbf{B} - \nabla P - \sum_a \nabla\cdot\boldsymbol{\Pi}_a + \sum_a \mathbf{M}_a$$

Taking the inner product $R^2\nabla\zeta\cdot$ above eq. and flux surface average < >

$$\sum_a m_a \left\langle n_a R \frac{\partial u_{a\zeta}}{\partial t}\right\rangle = -\left\langle \sum_a R^2\nabla\zeta\cdot\nabla\cdot\boldsymbol{\Pi}_a\right\rangle + \left\langle R^2\nabla\zeta\cdot\sum_a \mathbf{M}_a\right\rangle$$

Using the axisymmetric relation $R^2B\nabla\zeta = F(\psi)\mathbf{b} - \mathbf{b}\times\nabla\psi$

$$\left\langle R^2\nabla\zeta\cdot\nabla\cdot\boldsymbol{\Pi}_a\right\rangle = 0$$

This means that toroidal drag force by magnetic field variation is zero for axisymmetric system, while it becomes important (so-called Neoclassical Toroidal Viscosity) if there is some asymmetry [40]. It is also noted that drift wave turbulence may drive toroidal rotation due to breaking of $\pm k_{//}$ symmetry by sheared **E** x **B** flow [41], which may be a cause of intrinsic rotation observed in in tokamak [42].

6. 2D Newcomb Equation for Peeling/Balooning stability : ELM

The energy integral W under $\nabla\cdot\xi=0$ can be expressed in a following form by using $X=\xi\cdot\nabla r$ and $V=r\xi\cdot\nabla(\theta-\zeta/q)$ in the flux coordinates (r, θ, ζ) with $r=[2R_0\int_0^\Psi(q/F)d\psi]^{1/2}$ [43], [1]

$$W_p = \frac{\pi}{2\mu_0}\int_0^a dr\int_0^{2\pi} d\theta\mathcal{L}(X,\frac{\partial X}{\partial\theta},\frac{\partial X}{\partial r},V,\frac{\partial V}{\partial\theta})$$

Absence of $\partial V/\partial r$ term leads to simpler Euler-Lagrange equation for V and its solvability condition on θ leads to the following two-dimensional Newcomb equation for X.

$$\frac{d}{dr}\mathbf{f}\frac{d\mathbf{X}}{dr}+\mathbf{g}\frac{d\mathbf{X}}{dr}+\mathbf{hX}=0$$

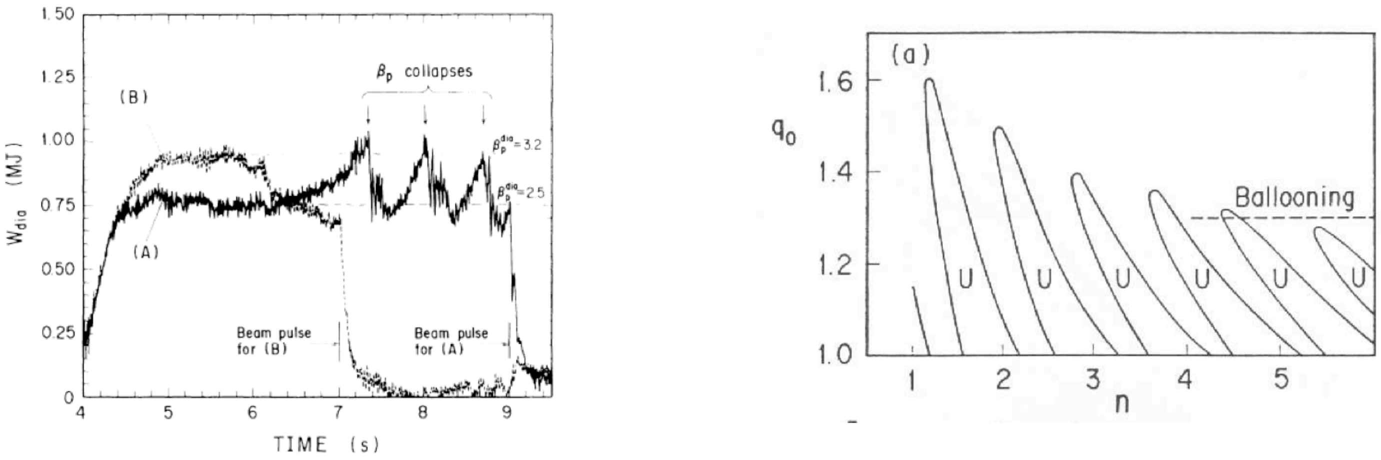
Here, $\mathbf{X}=(--,X_{-2},X_{-1},X_0,X_1,X_2,--)^t$ (t: transposed) where X_m is Foulier component of X and **f**, **g**, **h** are constant matrices.

MARG2D [43] solve this 2D Newcomb equation for the analysis of peeling modes with high n numbers. Here, Peeling mode is an external modes localized near the plasma edge driven by the finite edge current. This mode can be coupled to pressure driven ballooning mode and thought to be a cause of ELM (Edge Localized Modes) in tokamak.

7. 2D Infernal Modes as Central MHD Activity

If the magnetic shear is very low s=rdq/dr/q~0, radial mode separation becomes larger and radial mode coupling becomes weaker and standard ballooning mode theory base on dense radial mode coupling breaks down (Hastie, NF 1995).

And mode growth rate becomes oscillatory as a function of n (or toroidal wave number k_z) treated as a continuous parameter. Under such circumstance, intermediate integer n mode may become unstable even if lower n modes are stable. This low n internal pressure-drive mode is named as “infernal mode” by (J. Manickam, NF 1987)

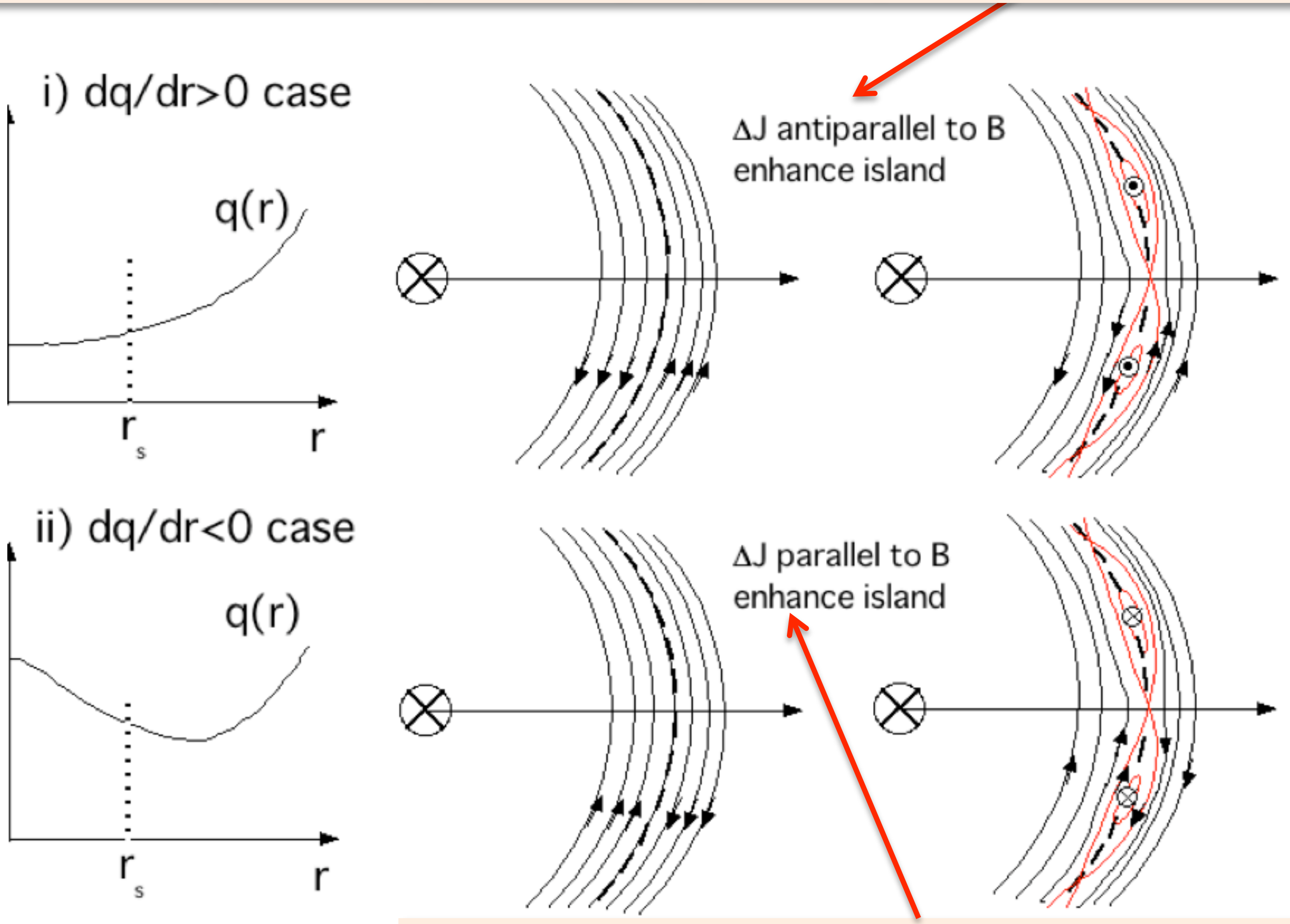


Ozeki, NF 1995 to explain βp collapse of JT-60 high βp discharges

8. Tearing and Neoclassical Tearing Modes

Kikuchi Physics and Fusion, Springer

Loss of bootstrap current by flattening of pressure gradient enhances island : NTM



Loss of bootstrap current by flattening of pressure gradient reduces island : stable to NTM

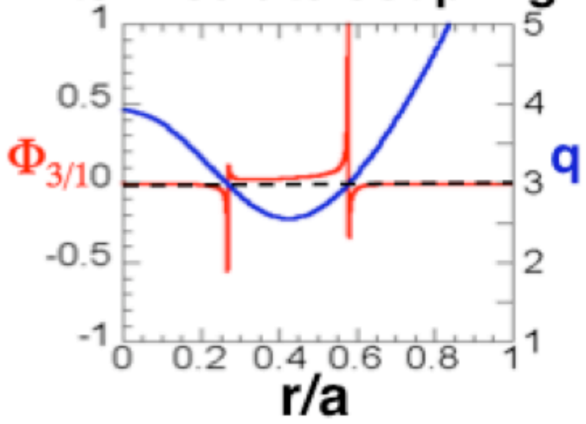
9. Double Tearing Modes

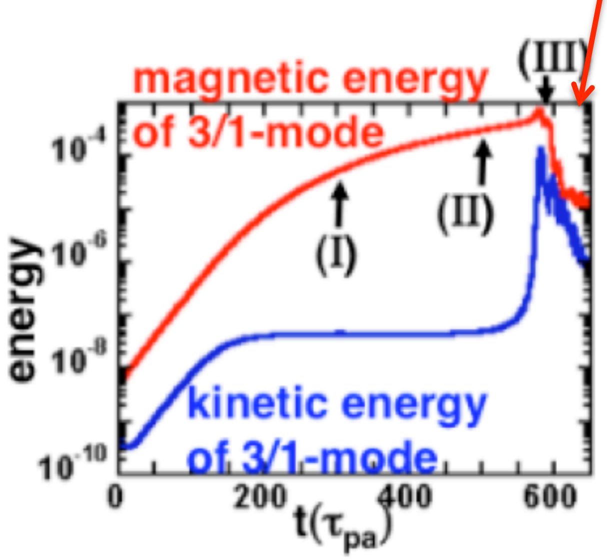
Ishii PRL (2002)

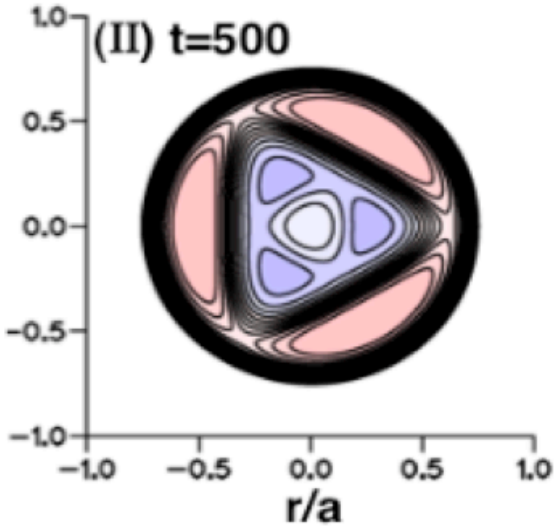
- For wide separation of singular surface, mode will not grow explosively.
- For intermediate separation, explosive growth happens later as point reconnection.

intermediate Δr

Intermediate coupling







Important implication for the plasma control is to pass through low m/n rational q_{min} as quick as possible under reduced pressure gradient and keep wider separation in quasi steady state.

10. Resistive Wall Modes

Early1990’s, wall stabilization was thought to be difficult.

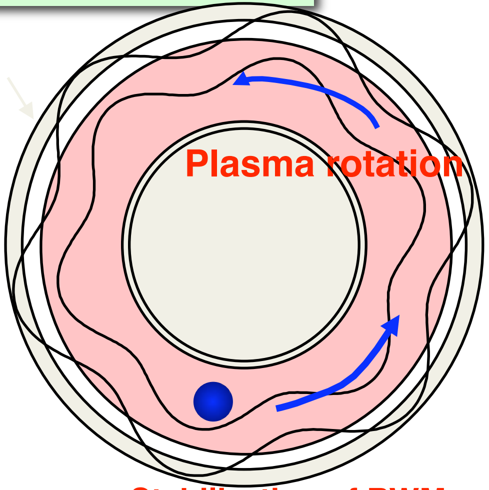
Ideal MHD can not be stabilized by slipping of plasma w.r.t. mode. **[Gimblett, N.F. 26(1986)617]**

Continuous damp :

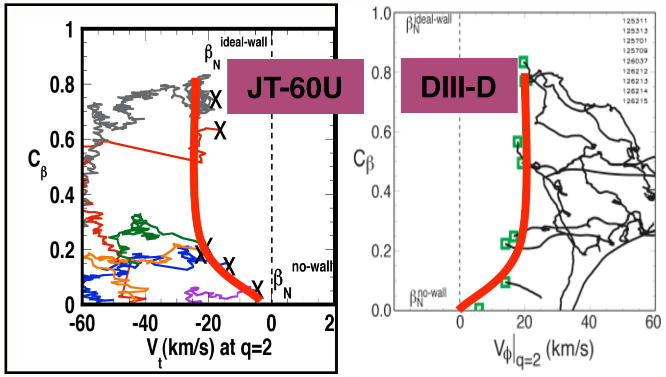
Shear Alfven wave has continuous spectrum –> Wave damping by phase mixing occurs

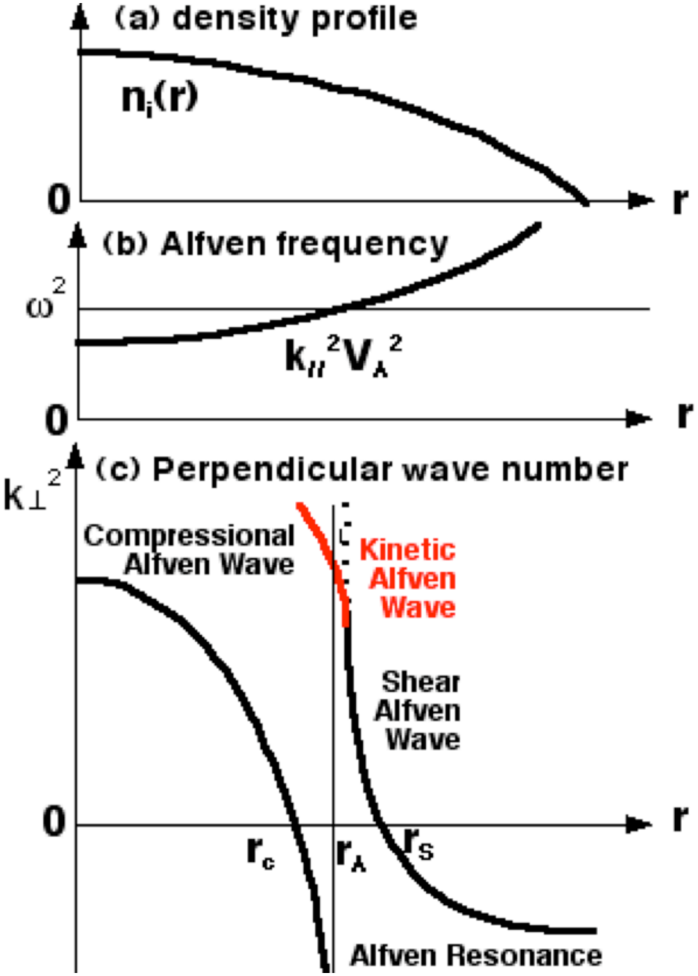
[1] Hasegawa-Chen , Kinetic Alfven Wave(KAW) (1974, first proposed as heating method)

RWM is fixed to wall



Stabilization of RWM





11. Toroidal Alfven Eigenmode (TAE)

Shear Alfven Wave may couple to High Energy Particles
-> But it will damp by phase mixing of shear Alfven Waves with different wave number

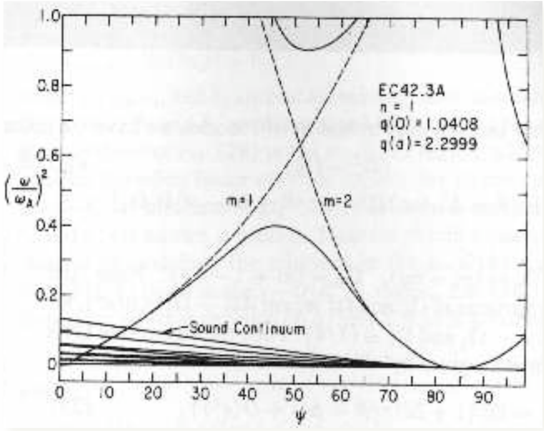
Coupling of different poloidal modes may eliminate Alfven Resonance.
-> Continuous damping will not work.

Toroidal coupling of m and m+1 produces frequency range Alfven resonance is prohibited.

$[\ (k^2_{//m} - (\omega/V_A)^2)\ (k^2_{//m+1} - (\omega/V_A)^2) - \varepsilon^2\ (\omega/V_A)^2 = 0$

$k_{//m} = (n-m/q)/R\ ,\ k_{//m} = -\ k_{//m+1}\ \ \text{-->}\ \ q = (m+1/2)/n$

Spinor : sin(mθ)+sin((m+1)θ)
=sin[(m+0.5)θ]cos(0.5θ)
Mobius band (periodic with two circulation) can not resonate.



F. Cheng predicted TAE.

Summary

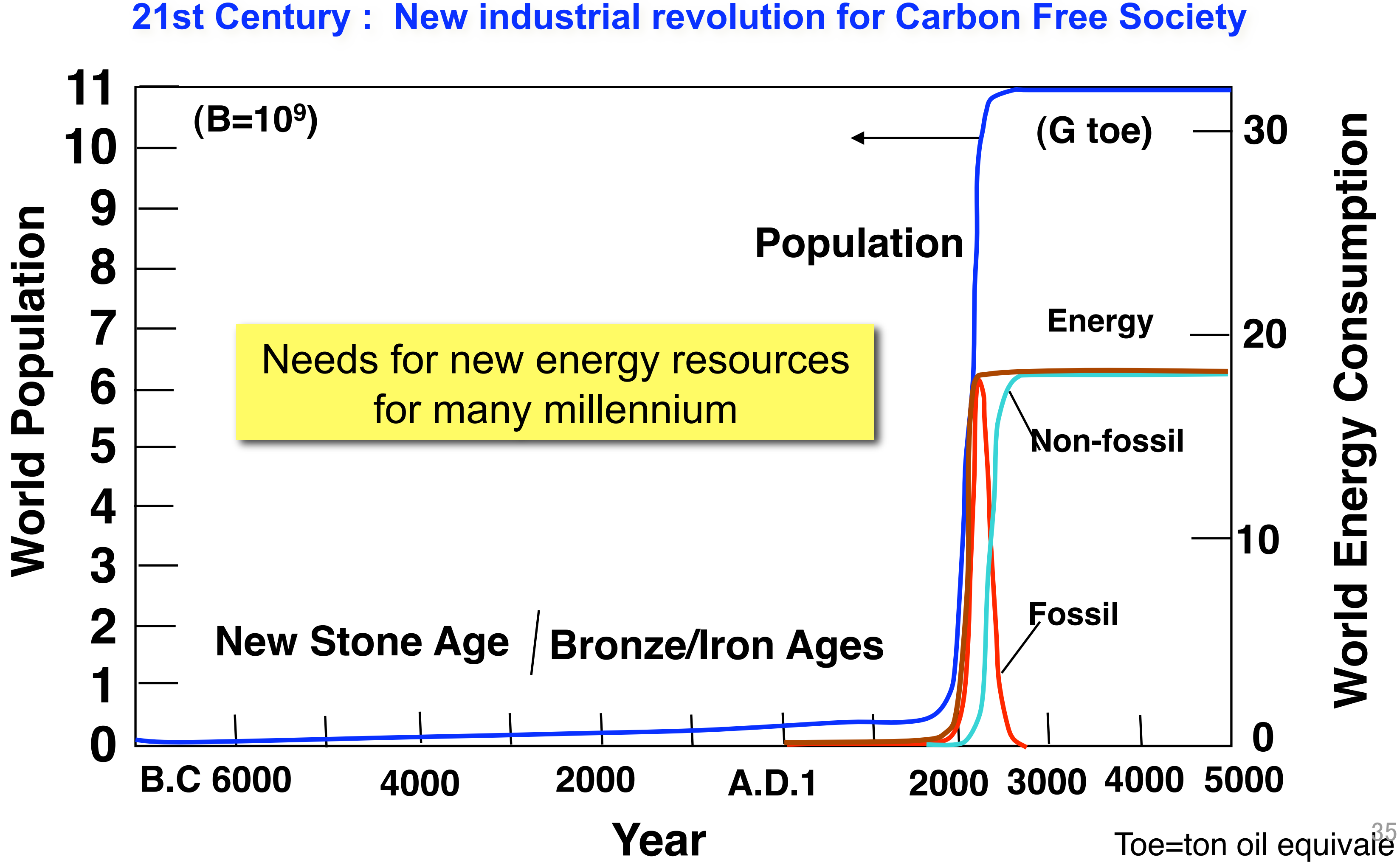
- Tokamak made a significant progress but it requires control of many phenomena.
- ITER is a test bed whether we can control them.
- There are enormous chance for young student to tackle to these issues.

Appendix Why Fusion

- Fossil Era will end in a moment
- Environmental problem
- Carbon free society
- Merit of fusion

A-1 Fossil Era will end in a Moment

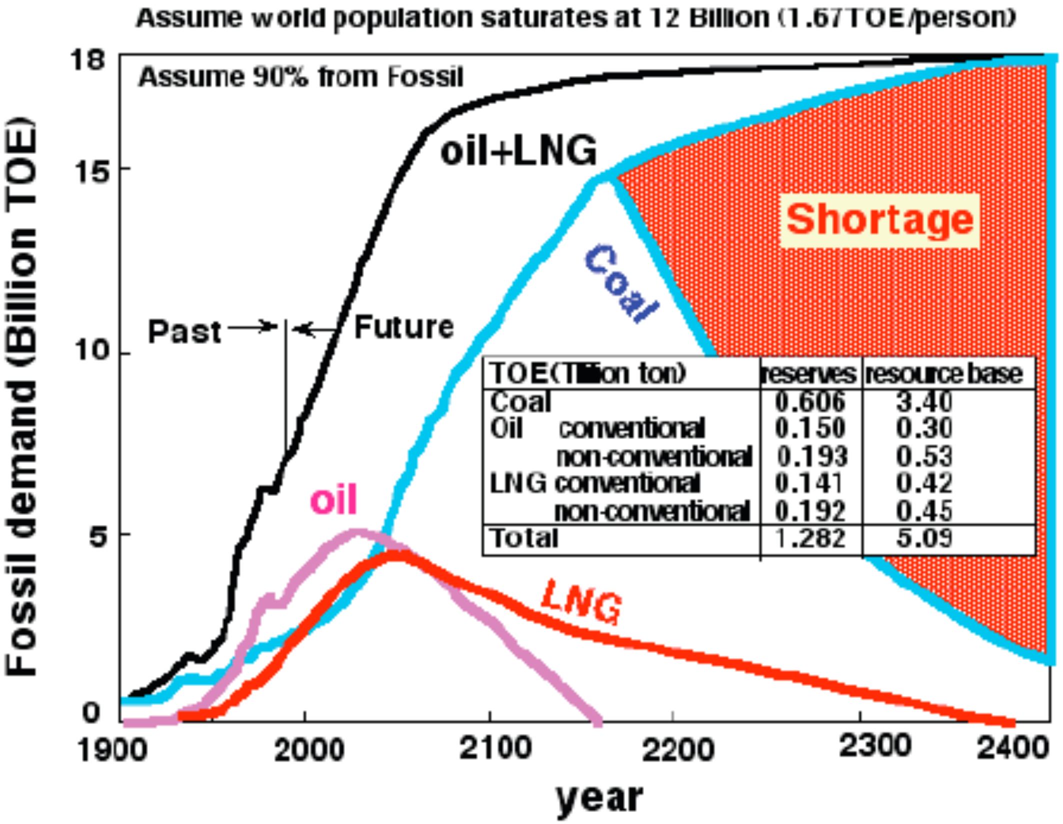
Present Civilization by Fossil Energy will end in a "moment
In 20th century, a BIG transition in population and energy consumption.



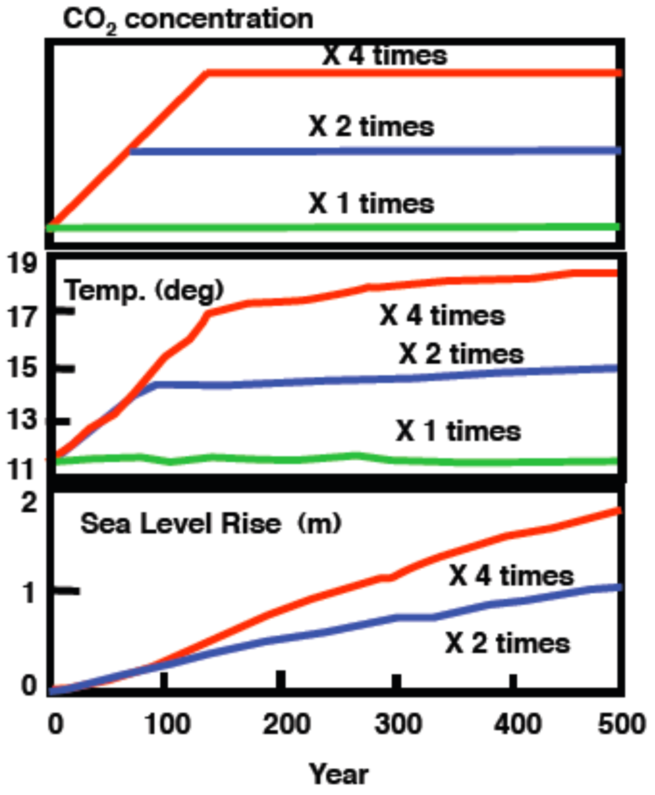
Toe=ton oil equivalent

A-2 Burn up of all fossil resource produce 4.8T Carbon ton

4.8T Carbon ton of CO_2 ~6.4 x CO_2 in atmosphere. Half will be absorbed by plants and sea. 3.2+1=4.2 times CO_2 in the atmosphere may give rise to 2m sea level rise.



TOE(Trillion ton)		reserves	resource base
Coal		0.606	3.40
Oil	conventional	0.150	0.30
	non-conventional	0.193	0.53
LNG	conventional	0.141	0.42
	non-conventional	0.192	0.45
Total		1.282	5.09



Y. Manabe, Symposium on Earth Frontier,1997

A-3 Carbon Free Society towards the end of 21st century

[Burn of fossil resources (5T Ton Oil Eq.) increases CO_2 concentration by 4 times and 2 m sea rise in 500y.]

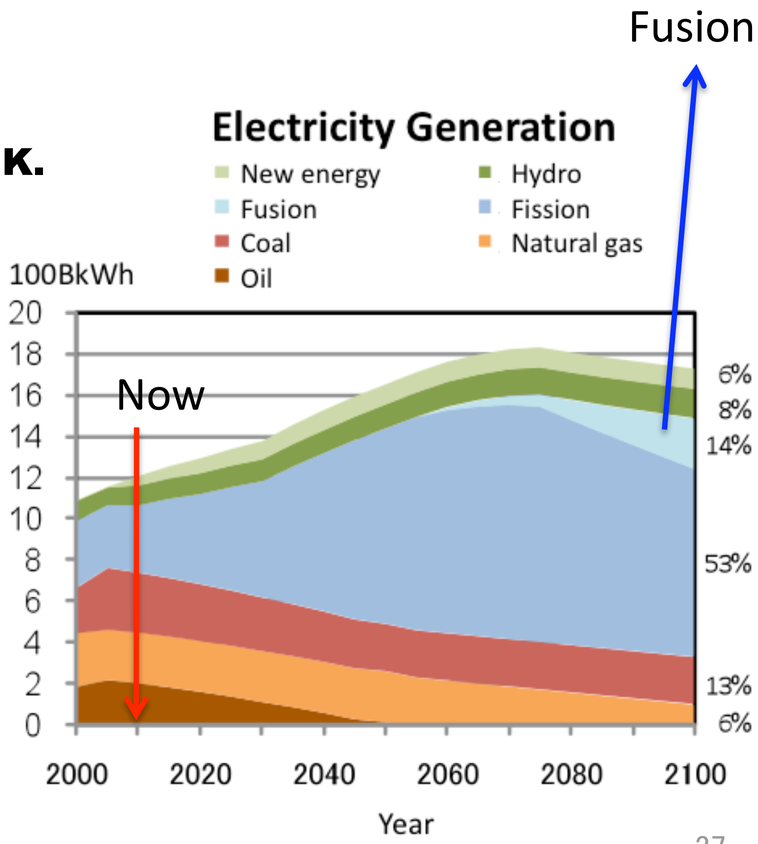
Carbon free system in all areas:
Transportation : gasoline to fuel cell/electric vehicles
Manufacturing : coal to hydrogen for steel deoxidization
House and Offices : gas, kerosene to electric

~80% of energy sources requirement may be electricity and hydrogen

Snowmass summer seminar1999 plenary talk by M.K.

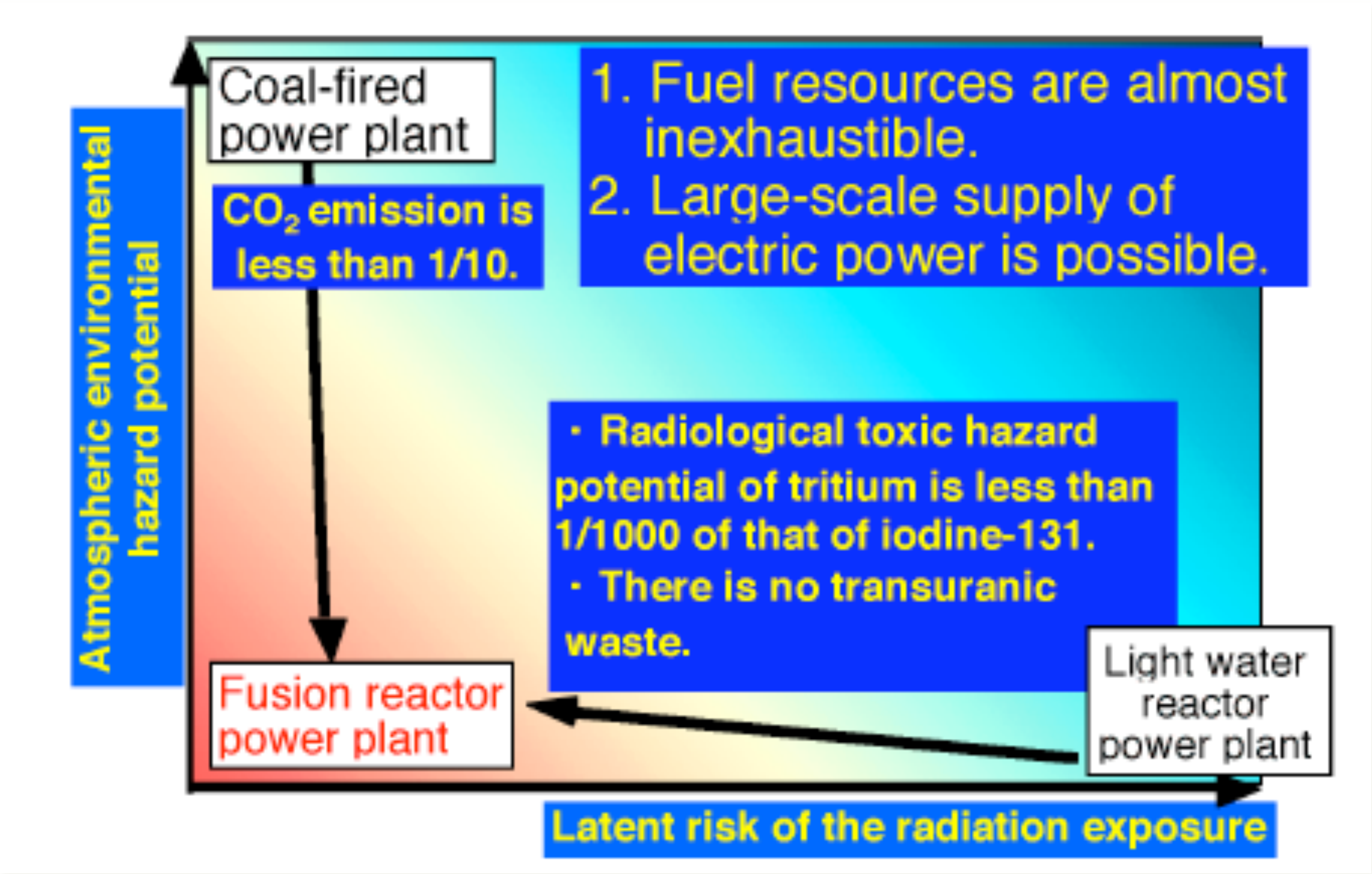
Richard J. Hawryluk Grant Logan Michael S. Mauel
Richard J. Hawryluk Grant Logan Mike Mauel
Co-Chairs of the 1999 Fusion Summer Study
October, 1999

	Fossil	Fission	Renewable	Fusion
Supply Stability	◎	◎	×	◎
Large Scale Supply	◎	◎	△	◎
Resource	○	◎	◎	◎
CO_2 Emission	×	◎	◎	◎
Waste	○	△	◎	○
Siting	◎	△	△	○
Safety(1/BHP)	○	△	◎	○
Cost	◎	○	△	△



JAEA 2100 Nuclear vision

A-4 Fusion’s Merit as Energy Source



CO_2 emission is less than 1/10.

1. Fuel resources are almost inexhaustible.
2. Large-scale supply of electric power is possible.

- Radiological toxic hazard potential of tritium is less than 1/1000 of that of iodine-131.
- There is no transuranic waste.

Fusion fuel inventory ~a few 10 s while fission fuel inventory ~ a few year