Plasma Production in a Small High Field Force-Balanced Coil Tokamak Based on Virial Theorem

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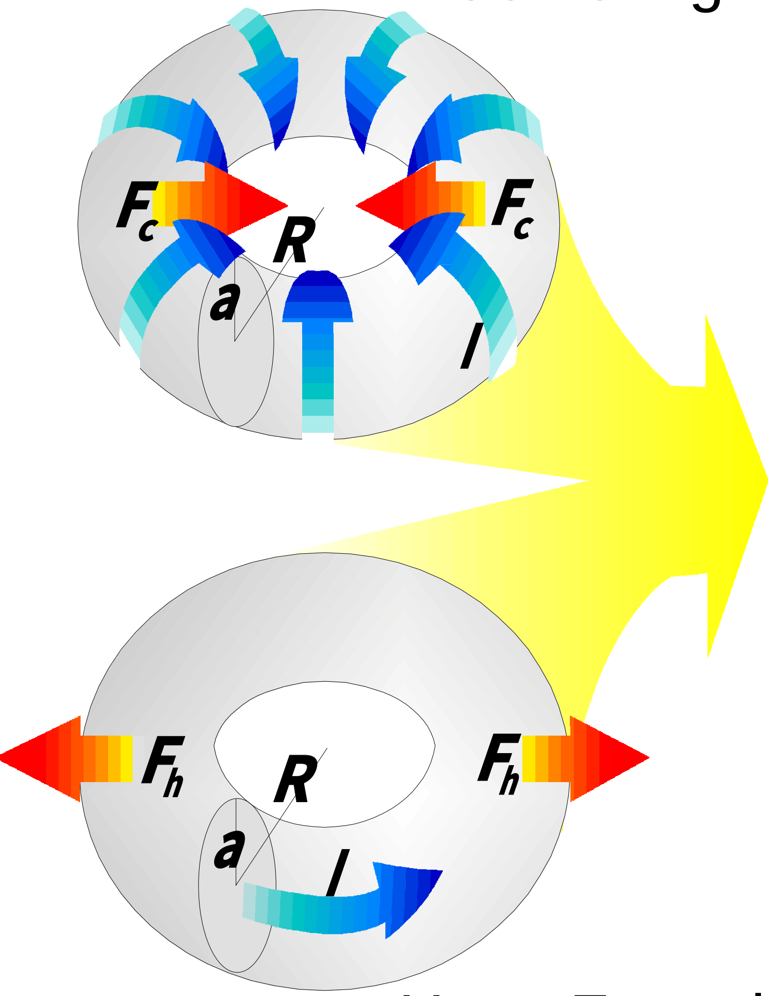
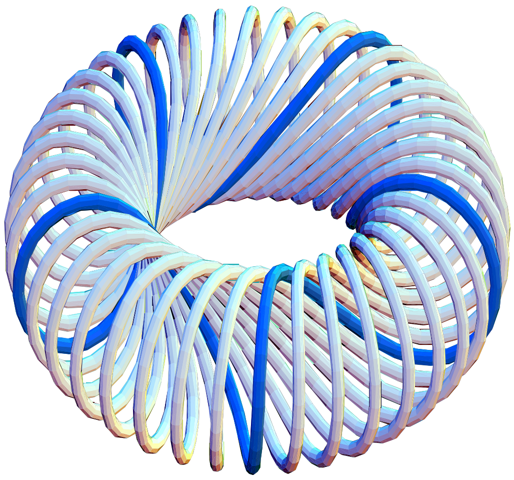
Introduction

- We studied the tokamak with the Force-Balanced Coils which are hybrid helical coils of OH and TF coils and reduced the electromagnetic force.
- The virial theorem, which is derived only form the equilibrium, shows that the tension is required to hold the magnetic energy.
- The virial theorem in magnet systems is derived by the replacement of plasma pressure to stress.
- In this work, we extend the FBC by the virial theorem, and obtain the minimal stress condition.
- The new small tokamak based on the virial theorem is constructed and plasma production is started.

Principle of Force-Balanced Coil

Centering Force by Poloidal Current





Force-Balanced Coil

Centering force is much reduced,
but
stress distribution is not investigated.

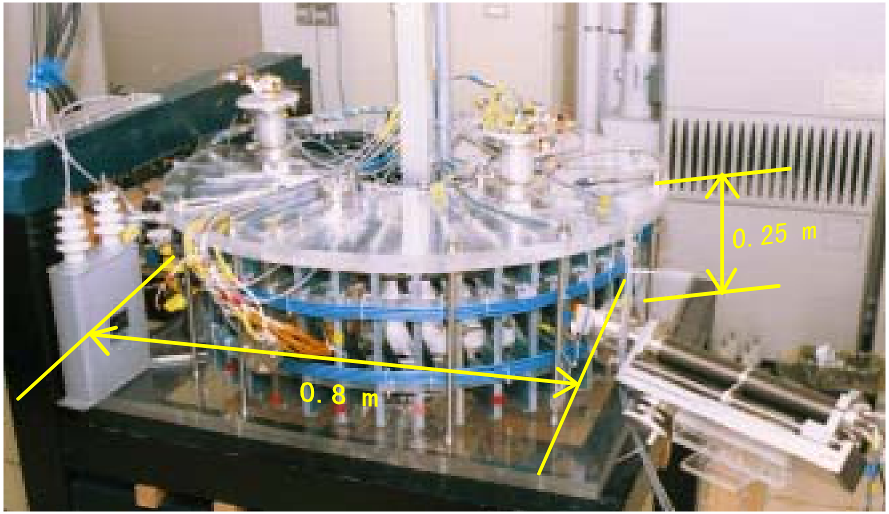
Hoop Force by Toroidal Current

Background

TODOROKI-I

Parameter	Value
Toroidal Field	1T
Plasma Current	10kA
Time of Discharge	4ms

- The error field by FBC made the control of plasma difficult
- The force of toroidal direction was reduced in FBC. Is it held in stress ?



- Reduction Error Field
- Estimation of Stress
- Application of Virial Theorem

Virial Theorem

$$\boldsymbol{j}\times\boldsymbol{B}+\nabla\cdot\mathsf{S}=0$$
$$\nabla\times\boldsymbol{B}=\mu_0\boldsymbol{j}$$
$$\nabla\cdot\boldsymbol{B}=0$$

$\boldsymbol{j}$: current density

$\boldsymbol{B}$: magnetic field

S: stress tensor

Equilibrium Eq.

$$\nabla\cdot(\mathsf{T}+\mathsf{S})=0$$
$$\mathsf{T}\equiv\frac{1}{\mu_0}\left(\boldsymbol{BB}-\frac{B^2}{2}\mathsf{I}\right)$$

T: Maxwell stress tensor

$$\int \mathrm{Tr}(\mathsf{T}+\mathsf{S})\,\mathrm{d}V=0$$
$$\int\sum_{i=1}^{3}\sigma_i\,\mathrm{d}V=\int\frac{B^2}{2\mu_0}\mathrm{d}V\equiv U_\mathrm{M}>0$$

σ_i : principal stress

$$\tilde{\sigma}\equiv\frac{V_\Omega}{U_\mathrm{M}}\sigma$$
$$\langle\sigma\rangle\equiv\frac{\int\sigma\,\mathrm{d}V}{V_\Omega}$$

$$\left\langle\sum_{i=1}^{3}\tilde{\sigma}_i\right\rangle=1$$

- Positive stress (tension) is required to hold the field.
- Uniform tension is favorable.
- Theoretical limit is determined.

$$\tilde{\sigma}_1=\tilde{\sigma}_2=\tilde{\sigma}_3=\frac{1}{3}$$

Application to Helical Coil

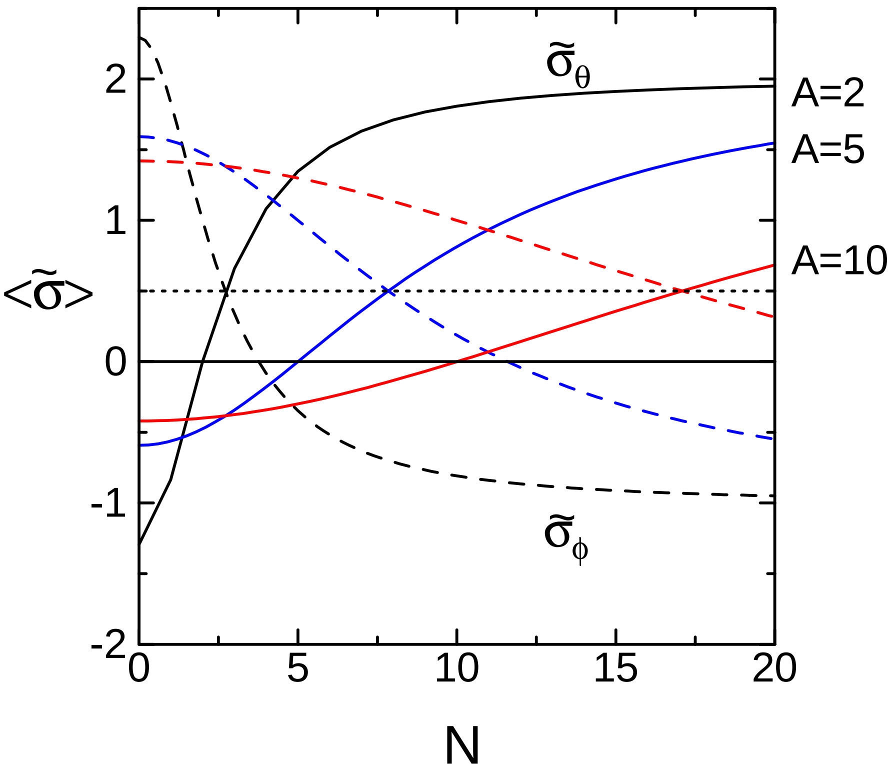
$$\langle\tilde{\sigma}_\theta\rangle = \frac{N^2 - A^2}{\dfrac{N^2}{2} + A^2\log 8A - 2A^2}$$

$$\langle\tilde{\sigma}_\phi\rangle = \frac{A^2\log 8A - A^2 - \dfrac{N^2}{2}}{\dfrac{N^2}{2} + A^2\log 8A - 2A^2}$$

$$\langle\tilde{\sigma}_\theta\rangle + \langle\tilde{\sigma}_\phi\rangle = 1$$

$N \equiv \dfrac{I_\theta}{I_\phi}$: Pitch of Coil

A : Aspect Ratio

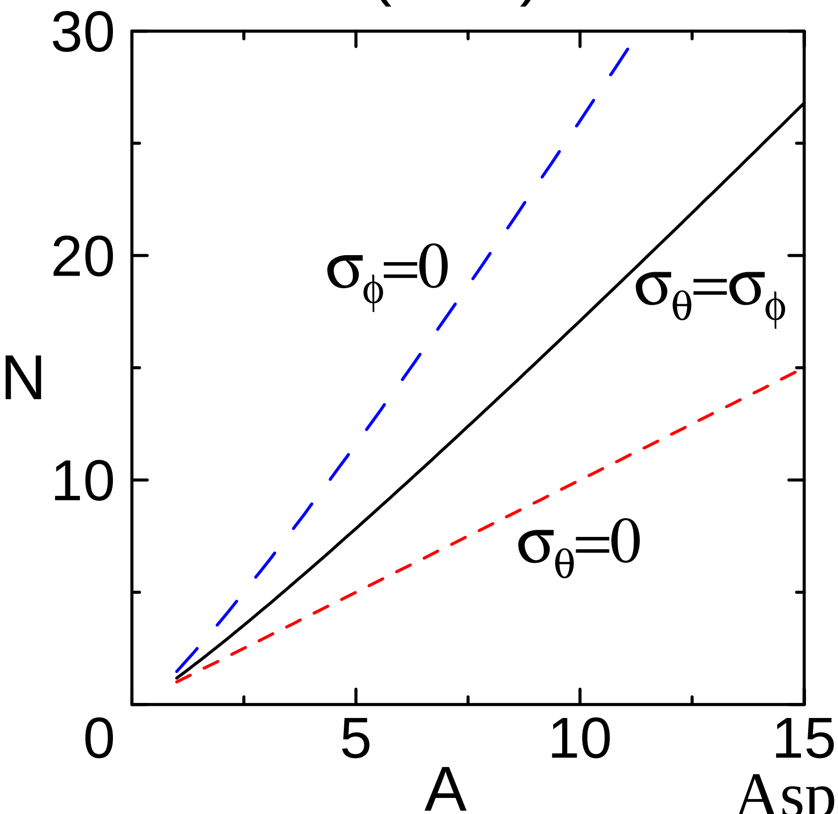


$\langle\tilde{\sigma}_\theta\rangle = \langle\tilde{\sigma}_\phi\rangle = \dfrac{1}{2}$ is optimal in energy.

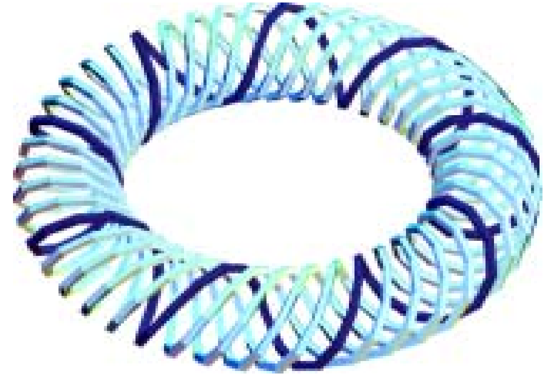
Virial-Limit Condition

Shape of Coils

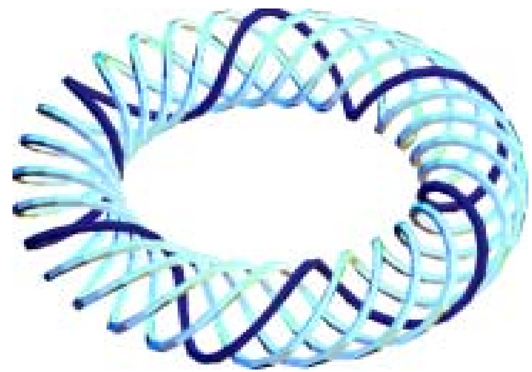
Relations of pitch number and aspect ratio of **Virial-Limit Coil** (**VLC**) etc.



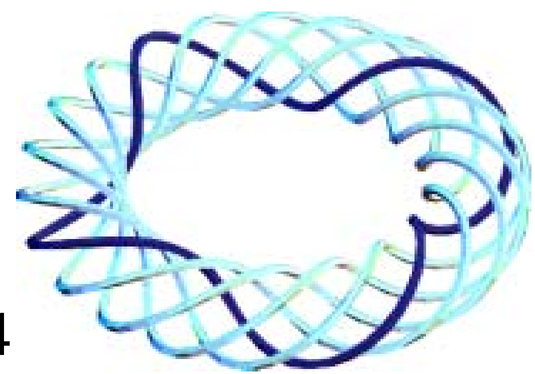
$\langle\sigma_\phi\rangle=0$
$N=9$
FBC



$\langle\sigma_\phi\rangle=\langle\sigma_\theta\rangle$
$N=6$
VLC



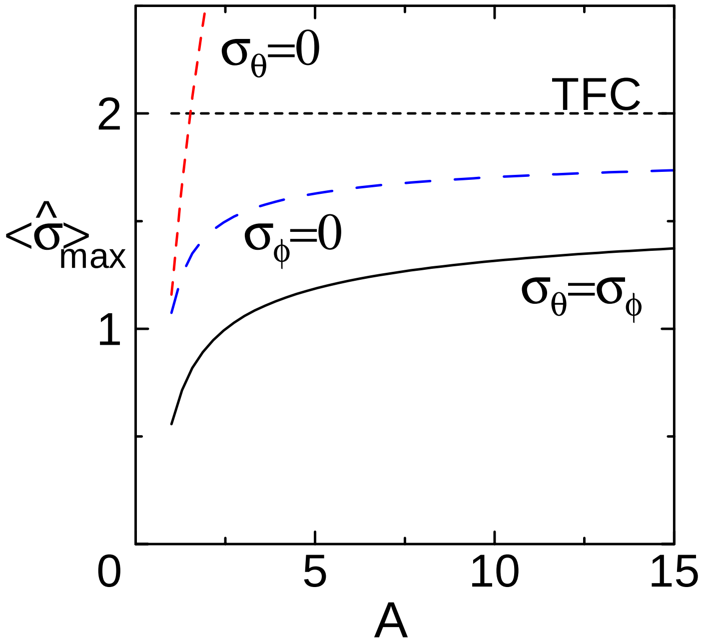
$\langle\sigma_\theta\rangle=0$
$N=4$



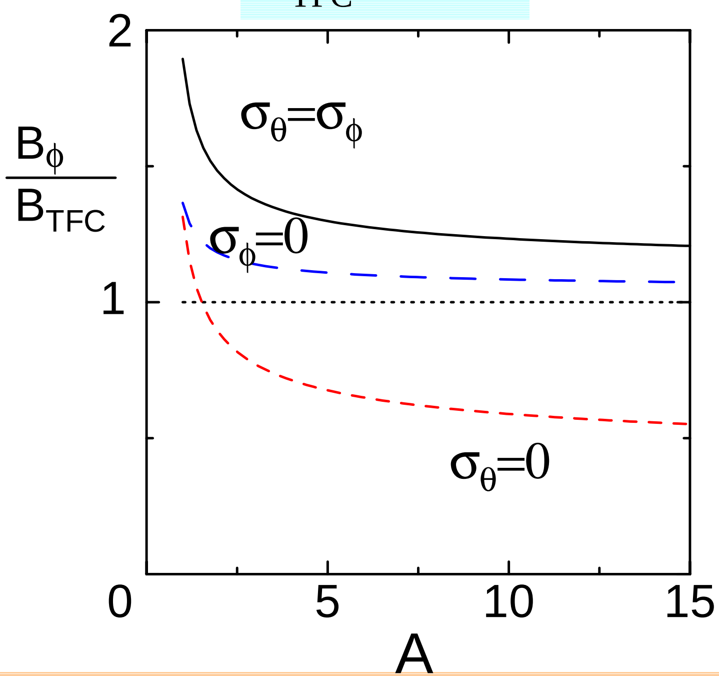
Aspect Ratio $A=4$

Comparison of Toroidal Field

$$\hat{\sigma} \equiv \frac{V_\Omega}{U_{TF}} \sigma$$



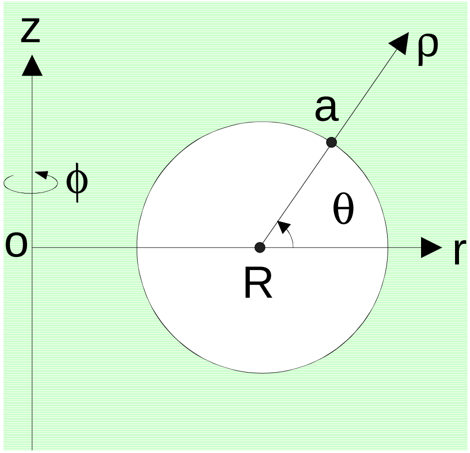
$$\frac{B_\phi}{B_{TFC}} = \sqrt{\frac{2}{\hat{\sigma}}}$$



- In the case of low aspect ratio, 1.5 times stronger magnetic field is created compared with traditional TF coil.

Toroidal Effect

Equilibrium of Magnetic Pressure and Stress



$$p \equiv \frac{B_\phi^2 - B_\theta^2}{2\mu_0}$$

$$u(r) \equiv a\int_R^r r'\,p(r')\mathrm{d}r'$$

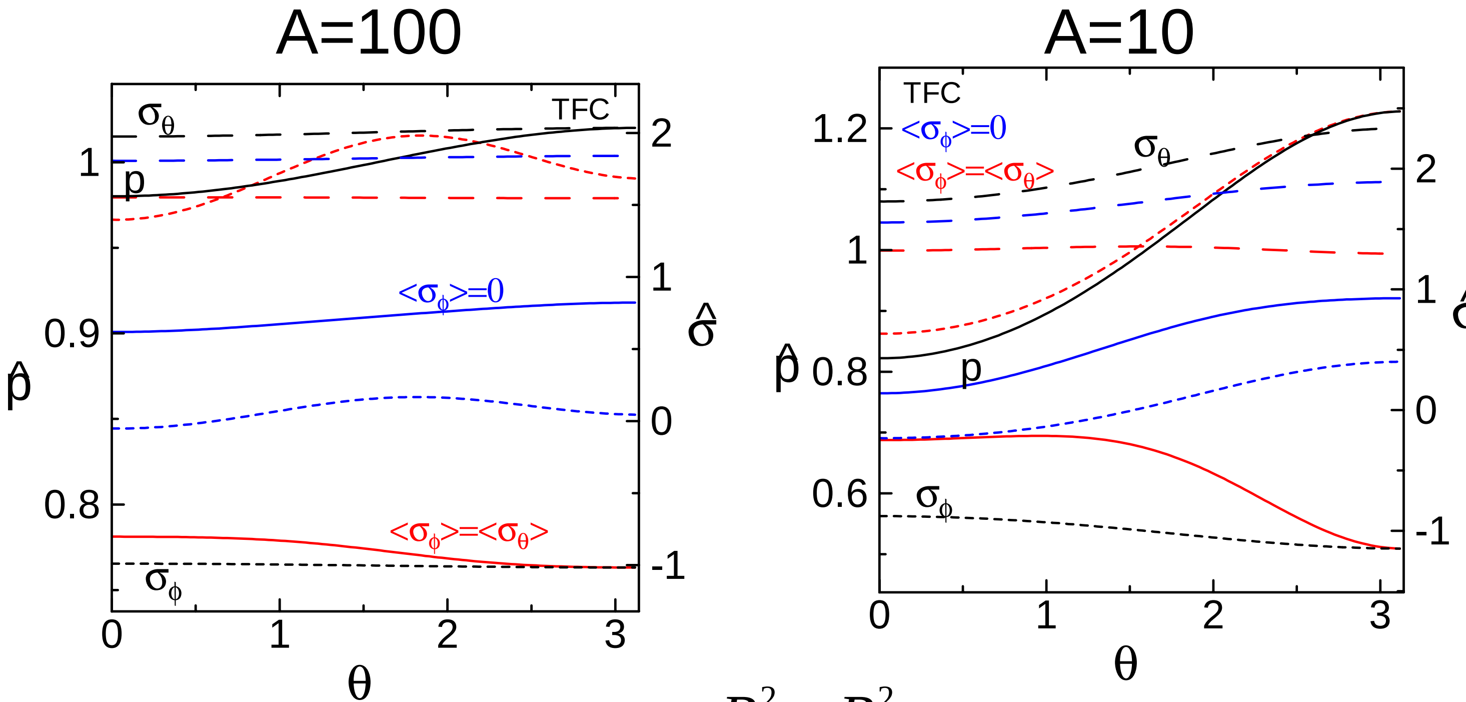
$$T_\theta = \frac{u}{(r-R)r}$$

$$T_\phi = \frac{arp}{r-R} - \frac{u}{(r-R)^2}$$

- Distribution of stress in the toroidal shell with circular cross section is derived analytically by use of magnetic pressure.

Distribution of Stress

(large aspect ratio)

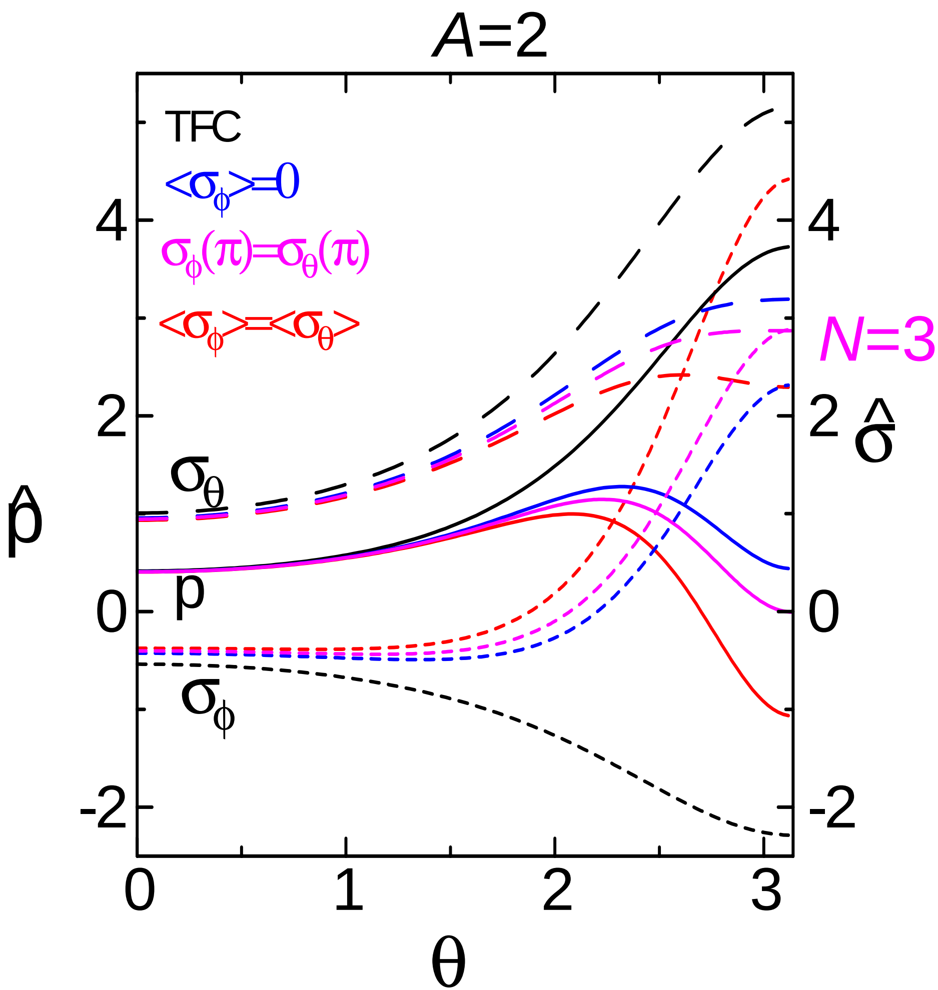


$$\hat{p} \equiv \frac{V_{\mathrm{T}}}{U_{\mathrm{M}}} \frac{B_\phi^2 - B_\theta^2}{2\mu_0}$$

- When *A*=100, distribution of stress is flat.
- There is no advantage of helical winding.

Distribution of Stress

(low aspect ratio)



- When A<10, distribution of stress is important.
- Assumption of large aspect ratio is not held.
- Optimal distribution is achieved to minimize the stress at $\theta=\pi$.

Uniaxial Stress Model

Equilibrium of Electromagnetic Force and Stress

$$\frac{\mathrm{d}T}{\mathrm{d}s} + \frac{F_u}{R} = 0$$

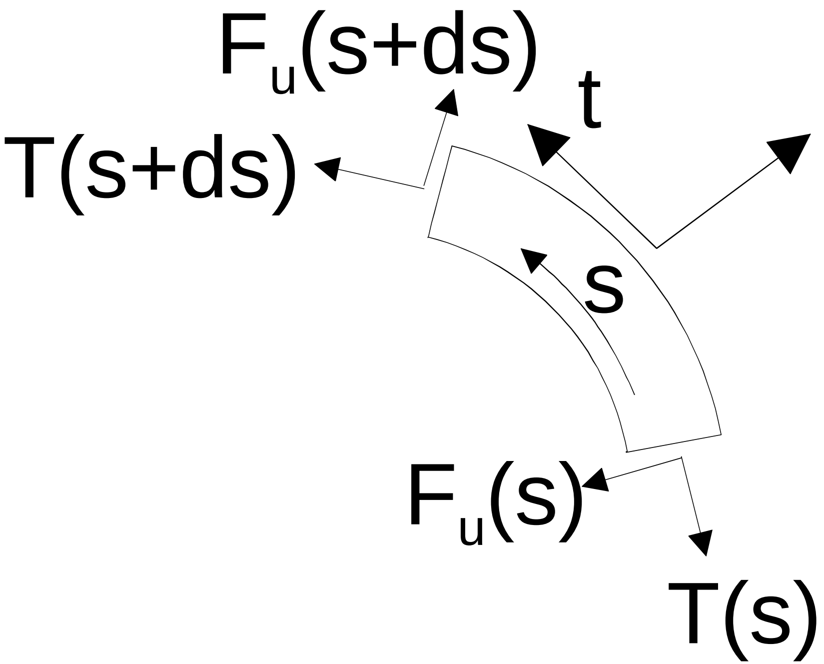
$$\frac{\mathrm{d}F_u}{\mathrm{d}s} + \frac{T}{R} + f_u = 0$$

T: tension, F: sharing force

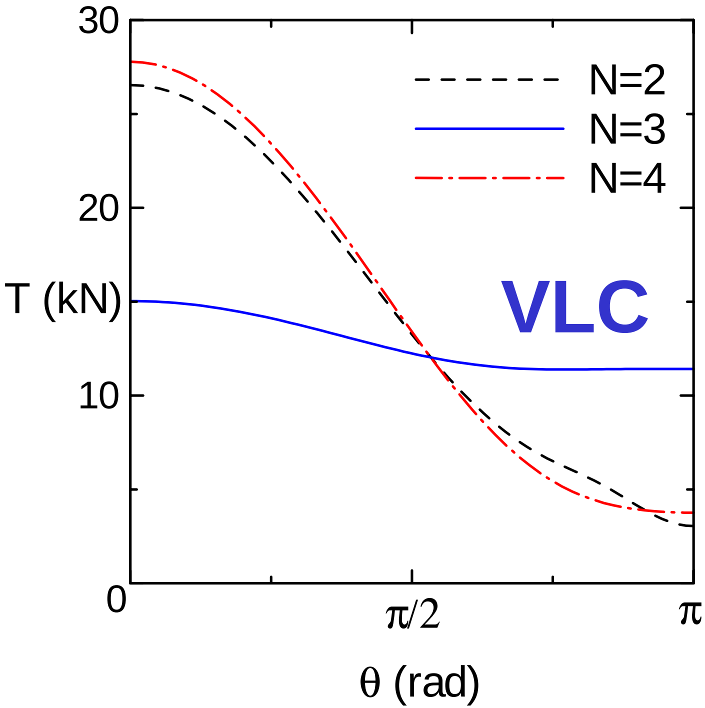
R: curvatur radius,

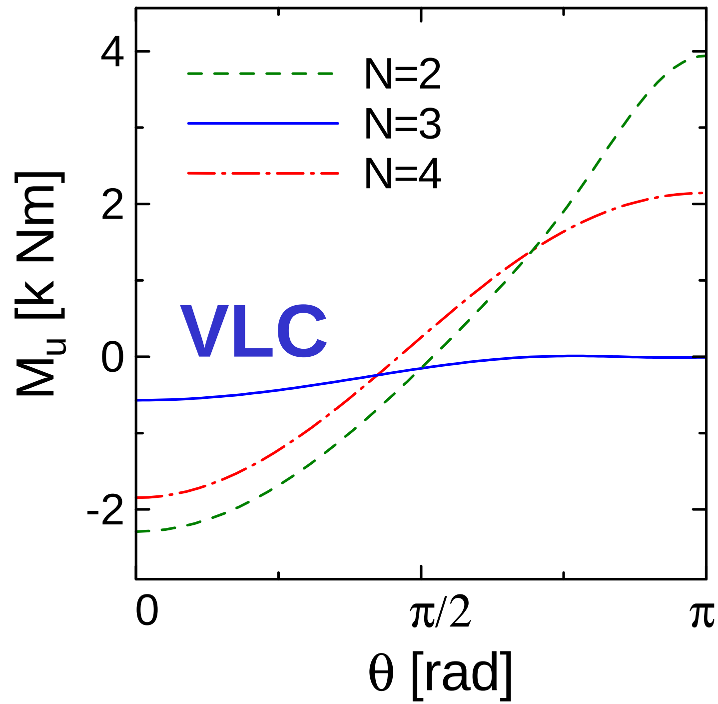
f: electromagnetic force

s: coordinate by length of coil



Tension and Bending Moment





- The tension of coil with pitch=3 is reduced and its distribution is flat.
- In the fat cable, the bending stress (proportional to bending moment) is important.
- The distribution of bending moment in the coil with pitch 3 is flat.

Stress Analysis of VLC

Why FEM analysis ?

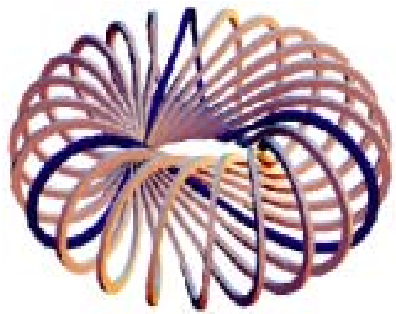
3D analysis is required because the virial-limit condition is obtained from the 2D shell model.

Conditions in FEM Analysis

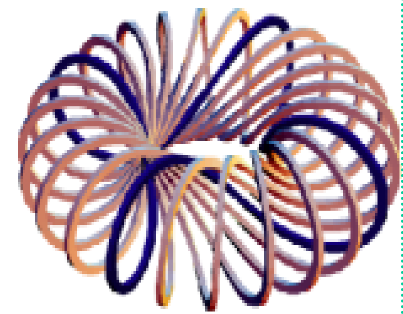
- 3D-Model with Electromagnetic Force
- Structure Analysis by FEM (NASTRAN) → Stress

Parameters	Value
Major radius	0.30 m
Minor radius	0.14 m
Aspect ratio	2.14
Pitch number N	24 turns
Coil current	96 kA/1 pole
Toroidal field	1.5 T
Cross section	380 mm^2
Young's modulus	1.26×10^5 N/mm^2
Poisson's ratio	0.33

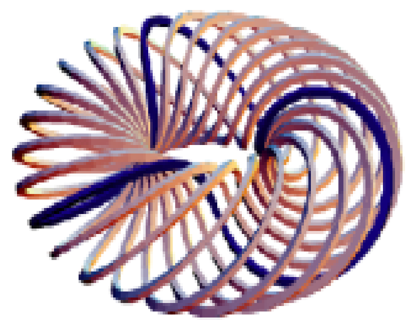
Current layer coincide with magnetic surface.



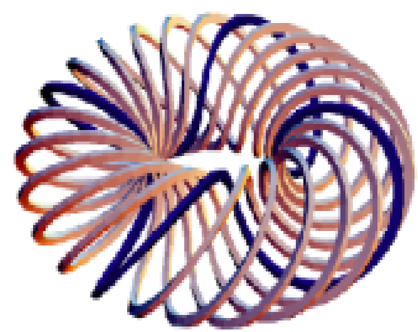
VLC with N=3



FBC with N=4



HC with N=3

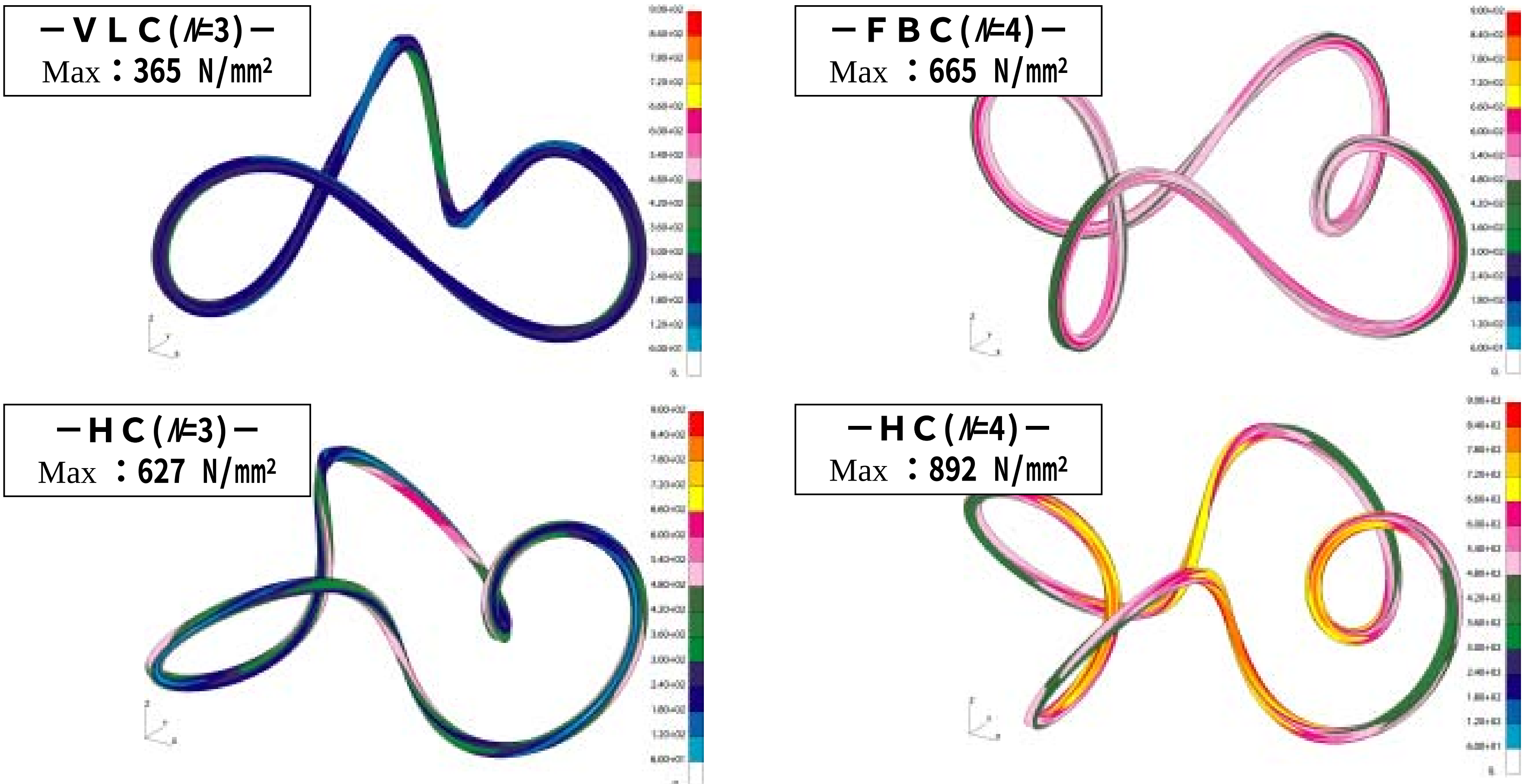


HC with N=4

Models in Analysis

Stress Analysis of VLC

Distributions of von Mises Stress



VLC(*N*=3) has no stress concentration and minimum stress compared with those of other coils.

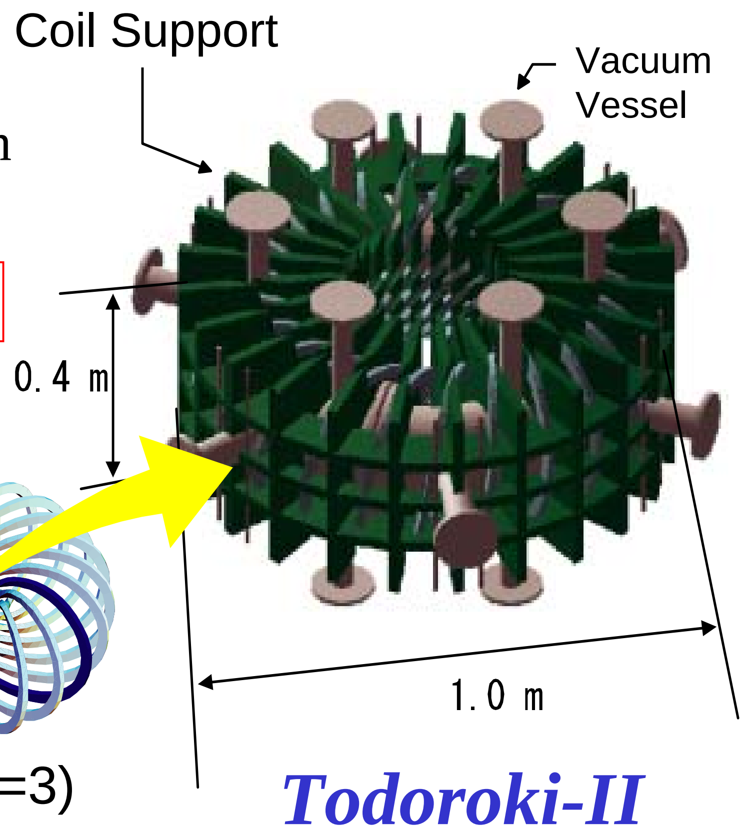
VLC realize both nearly uniform distribution of stress and minimum stress in 3D model

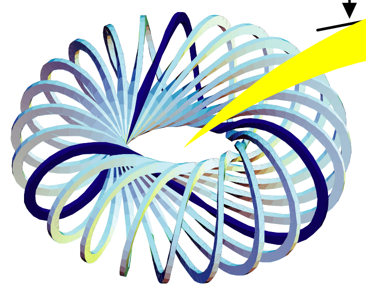
Outline of ＶＬＣ Tokamak

Outline of Design

Easy winding of coil → integer winding pitch
Large Plasma Volume → low aspect ratio

Coil orbit between their supports is nearly straight.





Parameters of Tokamak

Parameter	Value
Major radius(coil)	0.30 m
Minor radius(coil)	0.14 m
Aspect ratio	2.14
Pitch number	3
Pole number	8
inductance	1.3 mH
Major radius(vessel)	0.30 m
Minor radius(vessel)	0.08 m
Toroidal field	1.55 T
Minor radius(plasma)	0.07 m
Plasma current	40.0 kA

Materials

Coil:	high-tension Kevlar cross section of copper 12.72 mm^2
Vacuum Vessel:	SUS304
Coil Support:	GFRP (thickness 20 mm)

Vertical Field

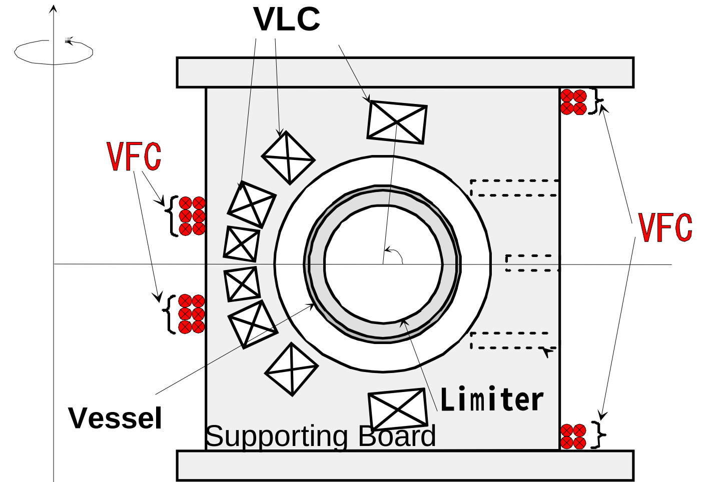
How to design Vertical Field Coil (VFC)

Controllability

→ minimization of mutual inductances to VLC.

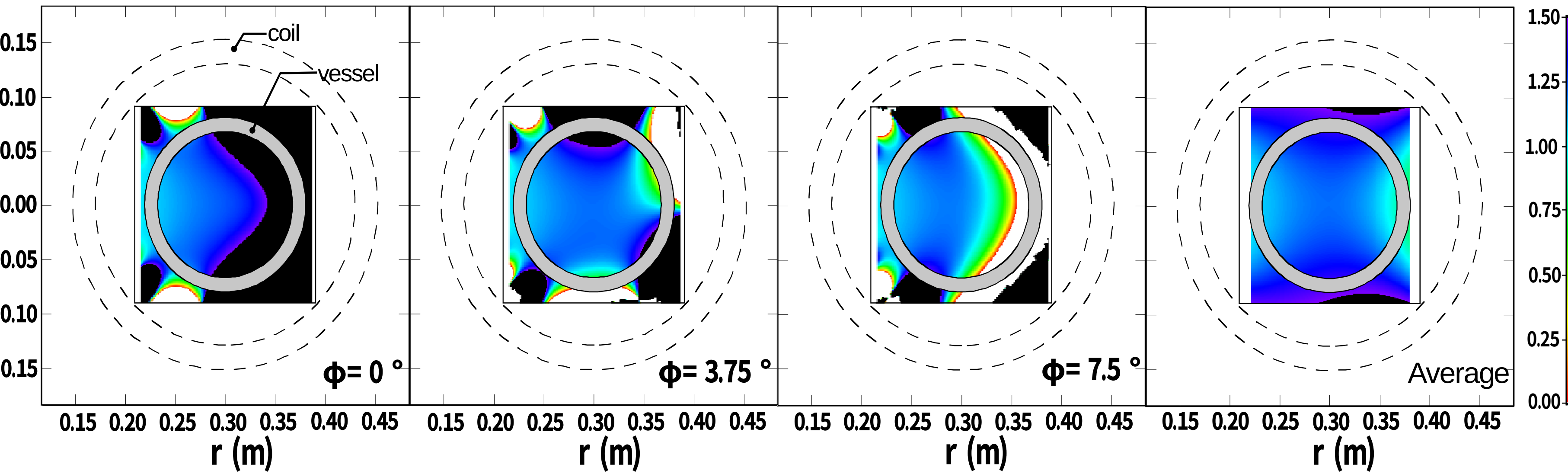
Positional Instability

→ n-index: n (stable condition: 0<n<1.5)



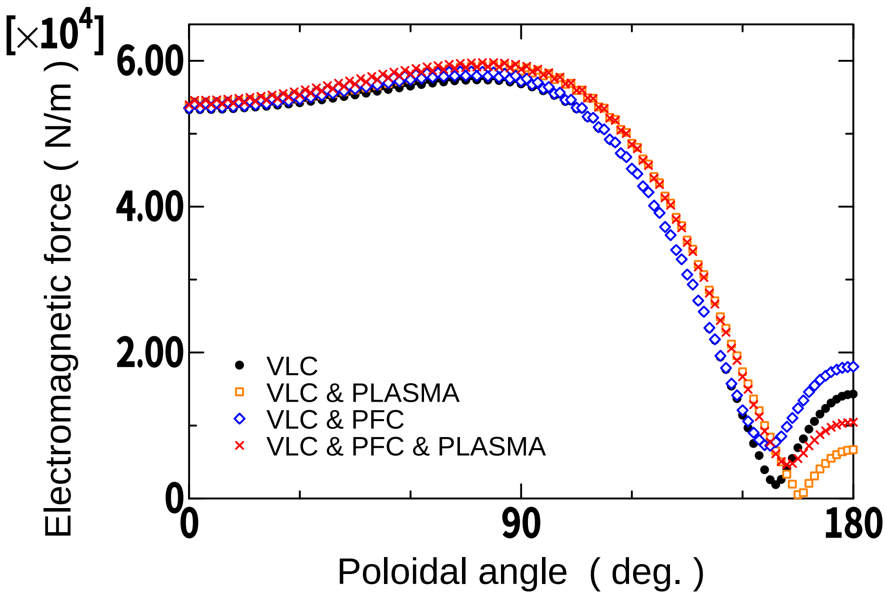
Positions of VFC on the cross sectio

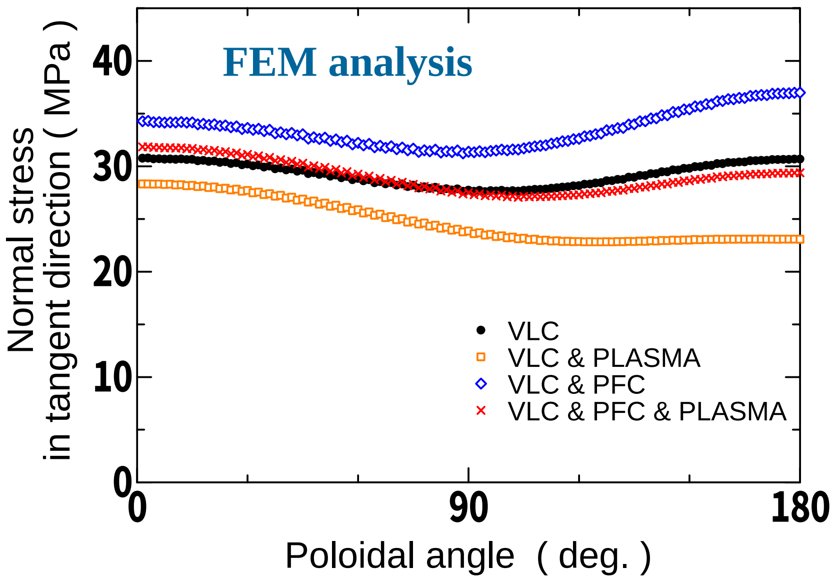
n-index



Stable in almost all region in the vacuum vessel

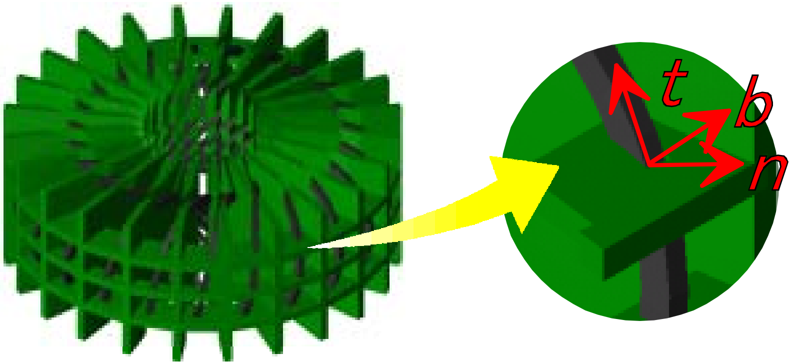
Effects of Plasma Current



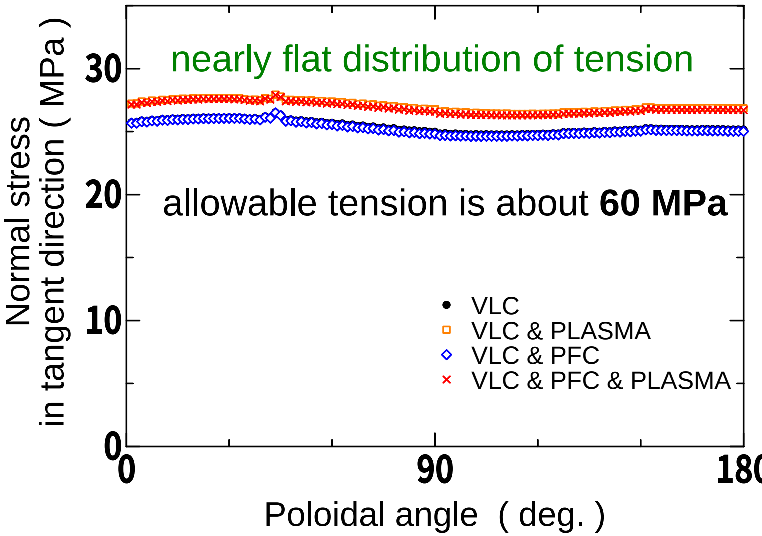


- In an actual system, electromagnetic force is modified by magnetic field produced by plasma and PF coil currents.
- Their influences are small enough to keep the advantage of VLC.

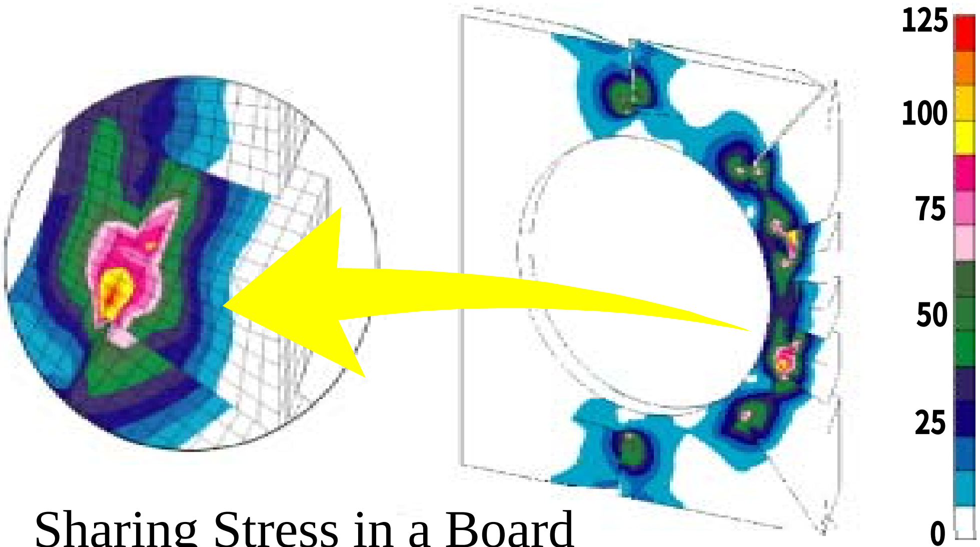
Stress with Supporting Board



Cables are supported by boards, but freely movable to the tangential direction ***t***.



Max: 124MPa<144MPa



Sharing Stress in a Board

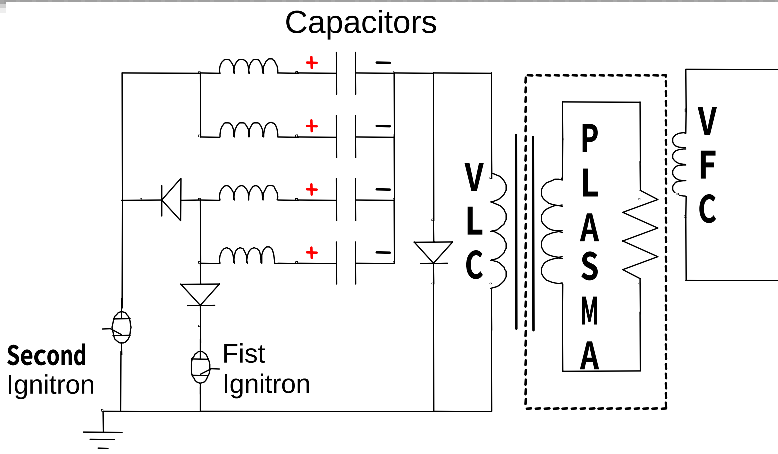
- Maximum stress in coils and boards is much smaller than their allowable stress.

Power Supply and Its Operation

Power Supply

Capacitor x 8	Capacitance :0.5 mF Max Voltage:12.5 kV
Inductance of VLC	1.3 mH

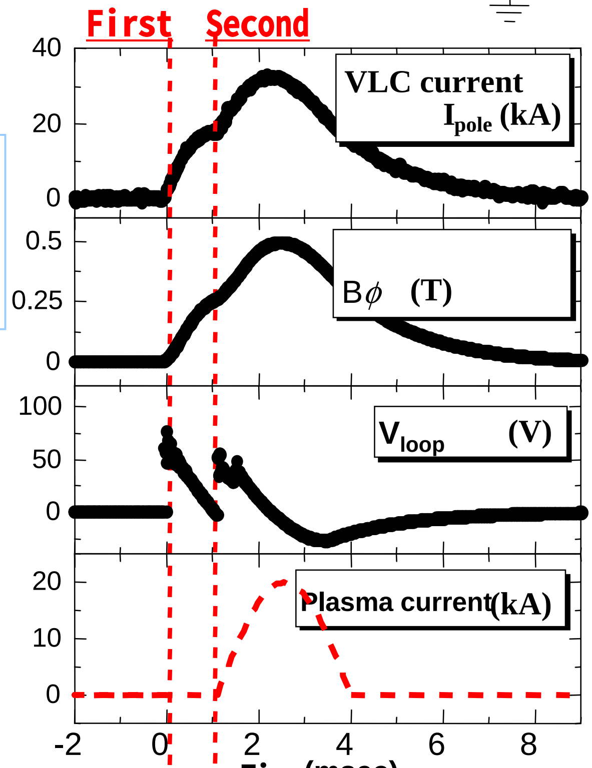
- Discharge period: about 10 msec



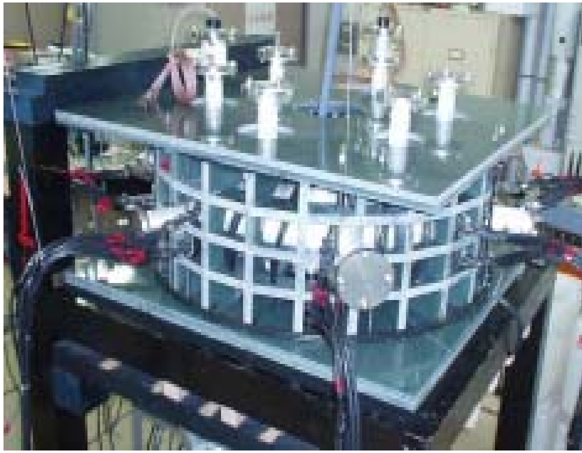
Operation

In the initial stage, there is no toroidal field because VLC is a hybrid coil of CS and TF coil.

First: Toroidal Field
Second: Loop Voltage



Todoroki-II



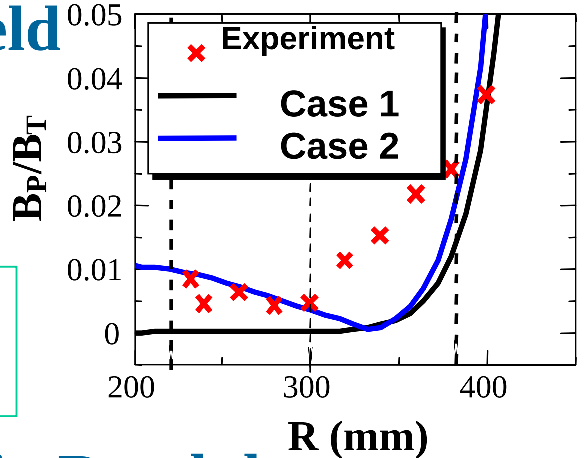
Breakdown Condition

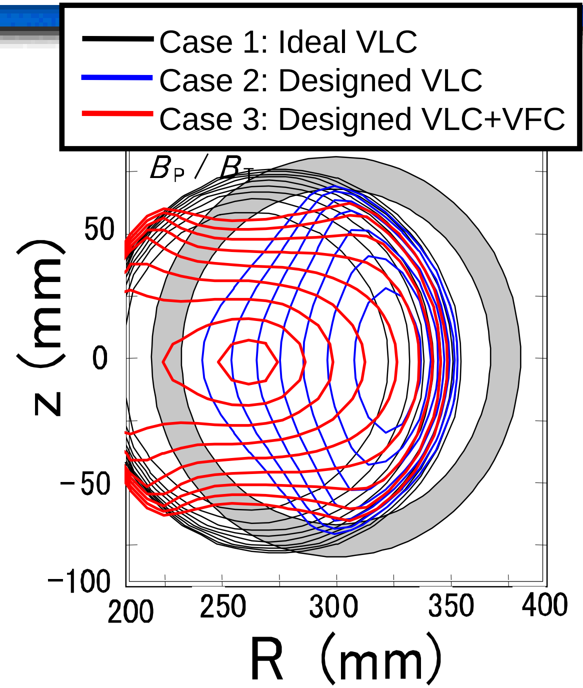
Normalized Poloidal Field

$$B_P / B_T = \sqrt{B_R^2 + B_Z^2} \,/\, B_T$$

Case 1: Ideal Coil Orbit

Case 2: Designed Coil Orbit





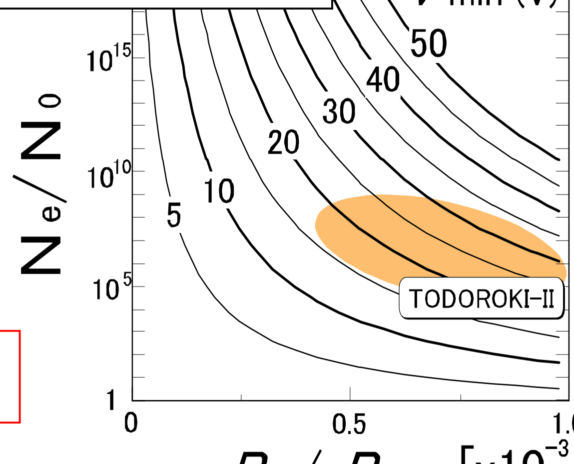
Required Loop Voltage in Breakdown

Next equation is obtained from Townsend Avalanche Model.

$$V_{\min} = 2\pi R_0 \frac{eA_2}{A_1} \log(N_e / N_0) \left(\frac{B_p}{B_T} \right) \Big/ X_P$$

(R_0 : major radius　　A_1, A_2 : constants of gas species
X_p : limiter radius　　n_e/n_0 : multiplication factor of electron)

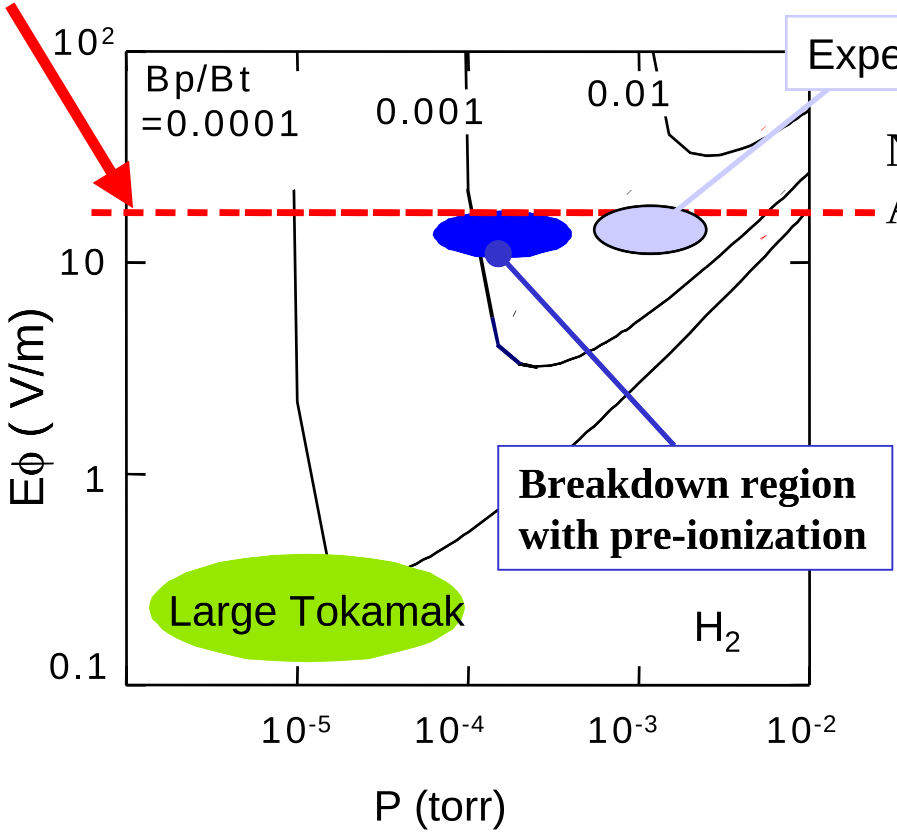
Loop voltage in case 1



Additional vertical field is required for breakdown.

Plasma Breakdown

Maximum Electric Field in Todoroki-II



Next equation is obtained from Townsend Avalanche Model.

$$\alpha = Ap\exp(-Bp/E)$$

$$\alpha^{-1} = L = 0.25 a_{eff} B_T / B_P$$

A, B: constants of gas species
p : gas pressure
E : toroidal electric field
$\mathbf{a_{eff}}$: limiter radius

Error fields by eddy current require pre-ionization.

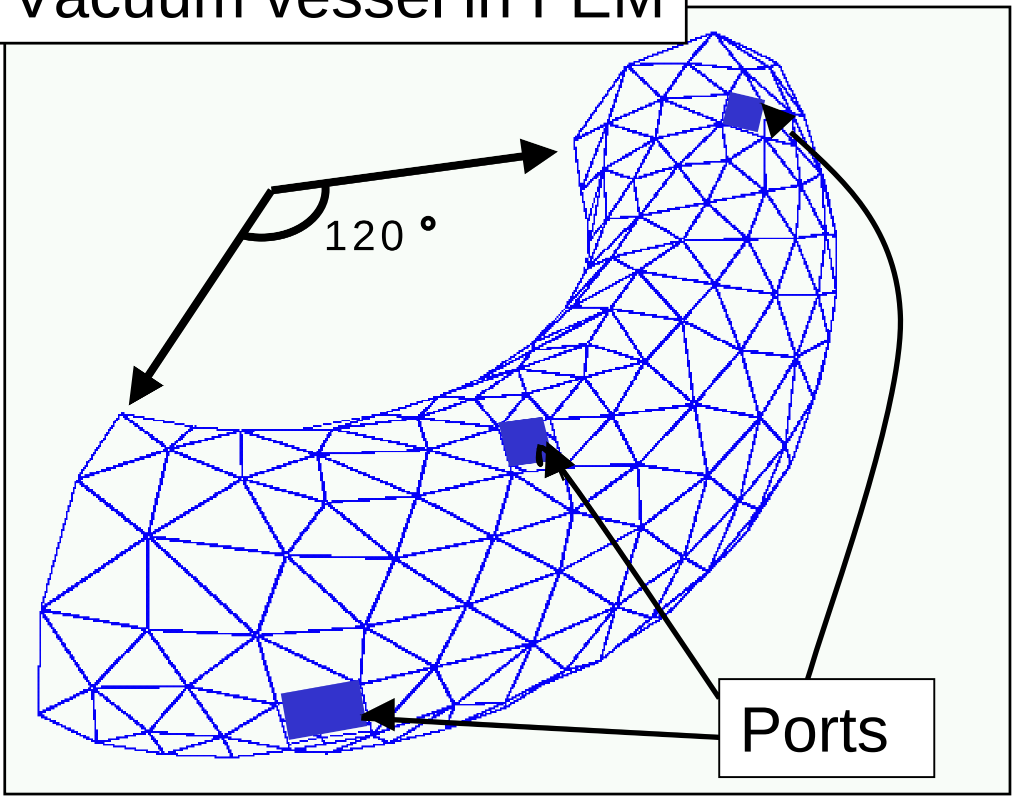
Eddy current analysis

$$A = \frac{\mu_0}{4\pi}\int_s \frac{J}{\rho} ds$$

J=∇×V V: current vector potential

P : distance between source and observed points.

Vacuum vessel in FEM



Vacuum vessel

material sus304

width 2.8×10^{-3}m

resistivity 7.2×10^{-7} Ω･m

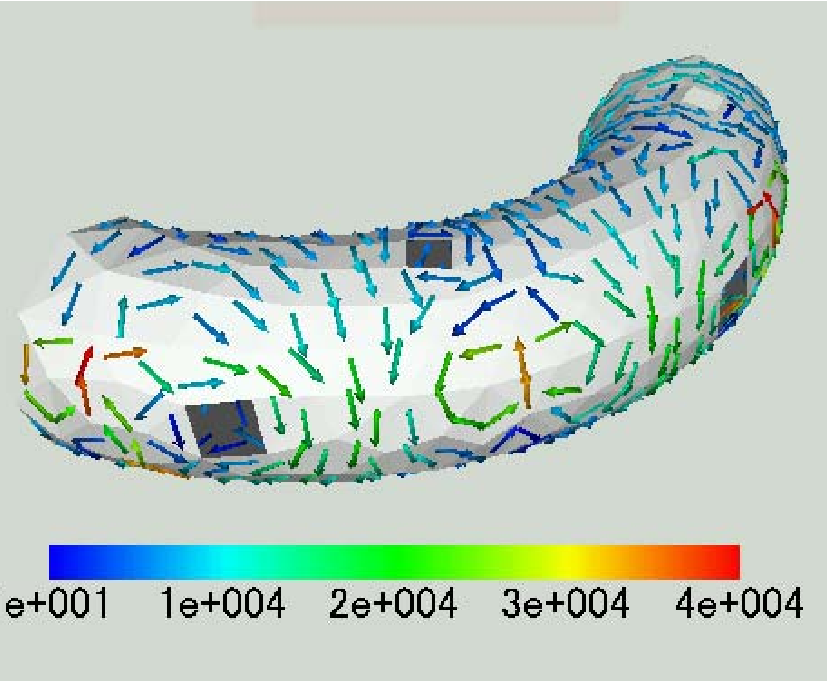
major radius 0.30 m

minor radius 0.082 m

A vacuum vessel is constructed by 3 insulated blocks, and has a periodicity of 120 degree.

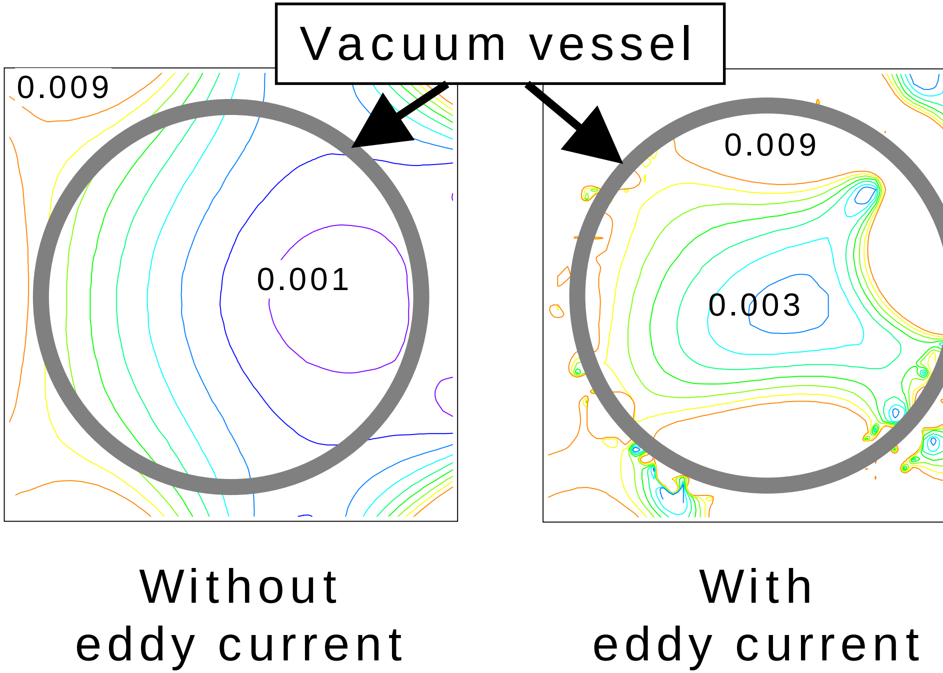
Eddy current and error field

A result by FEM (EDDYCAL)



Normalized poloidal field

$$B_P / B_T = \sqrt{B_R^2 + B_Z^2} / B_T$$



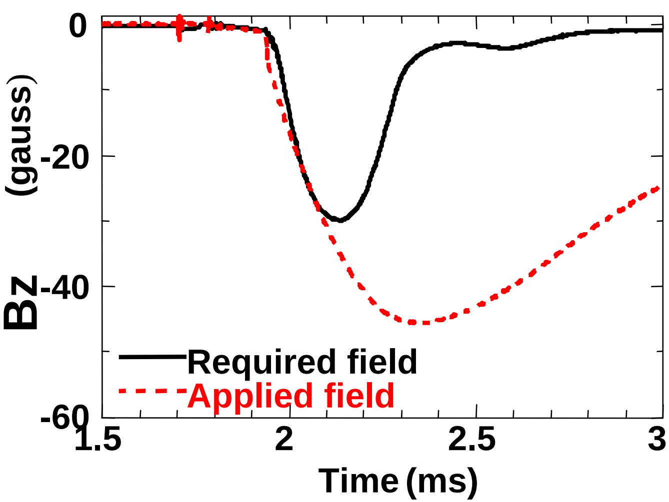
Error fields by eddy current prevent plasma breakdown.

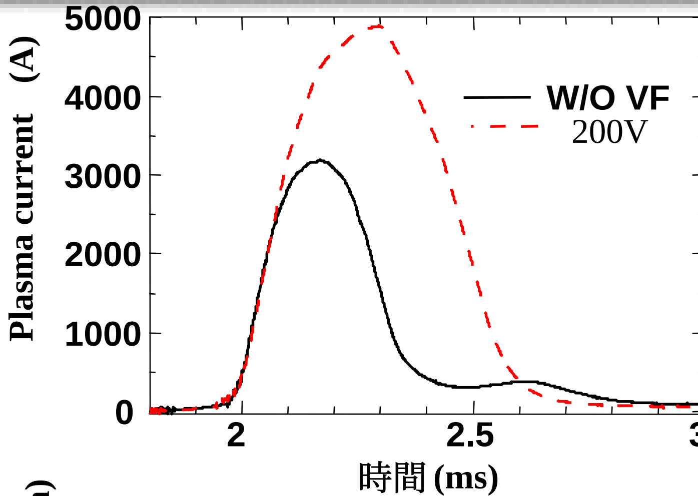
Plamsma position control

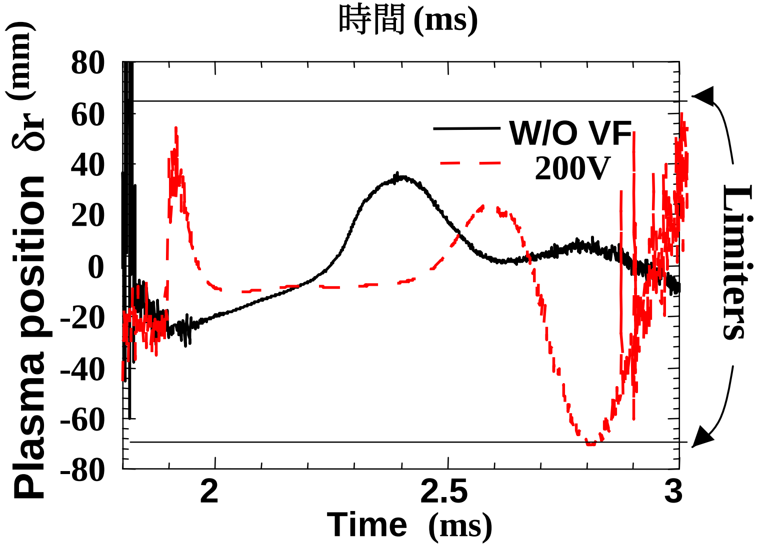
- **Vertical field for equilibrium**

$$B_z(r) = -\frac{\mu_0 I_p}{4\pi R}\left(\ln\frac{8R}{a} + \frac{l_{in}}{2} - \frac{3}{2} + \beta_p\right)$$

I_p : plasma current
l_{in} : plasma internal inductance
β_p : poloidal beta

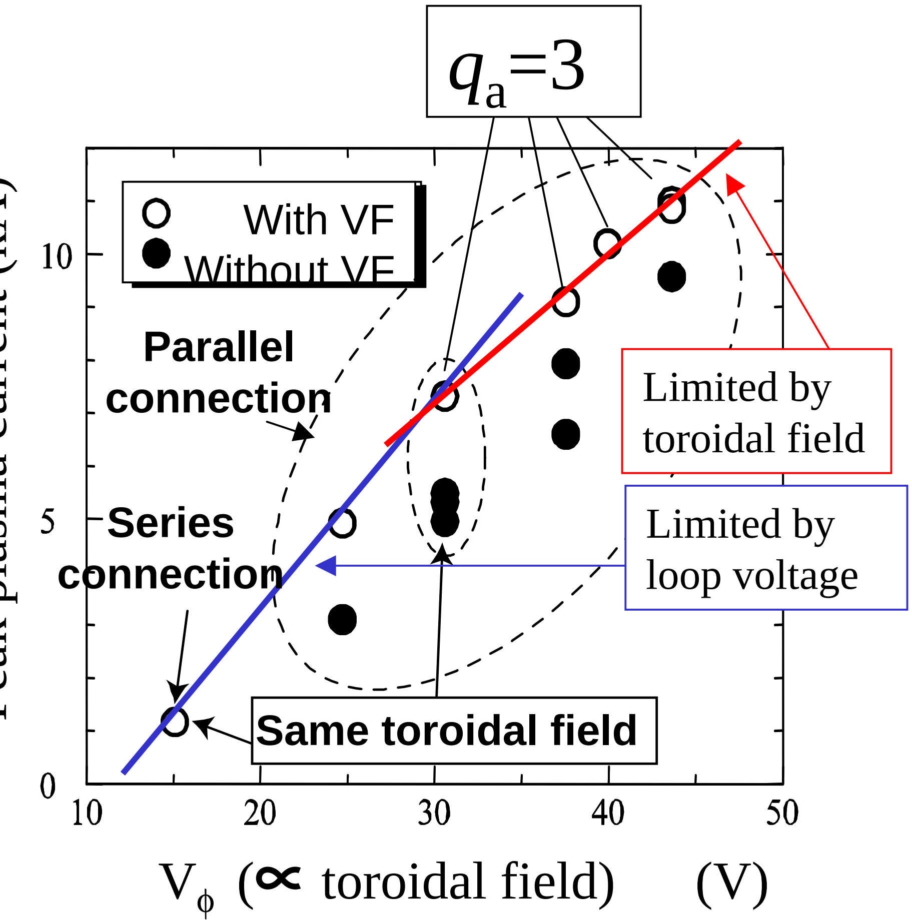




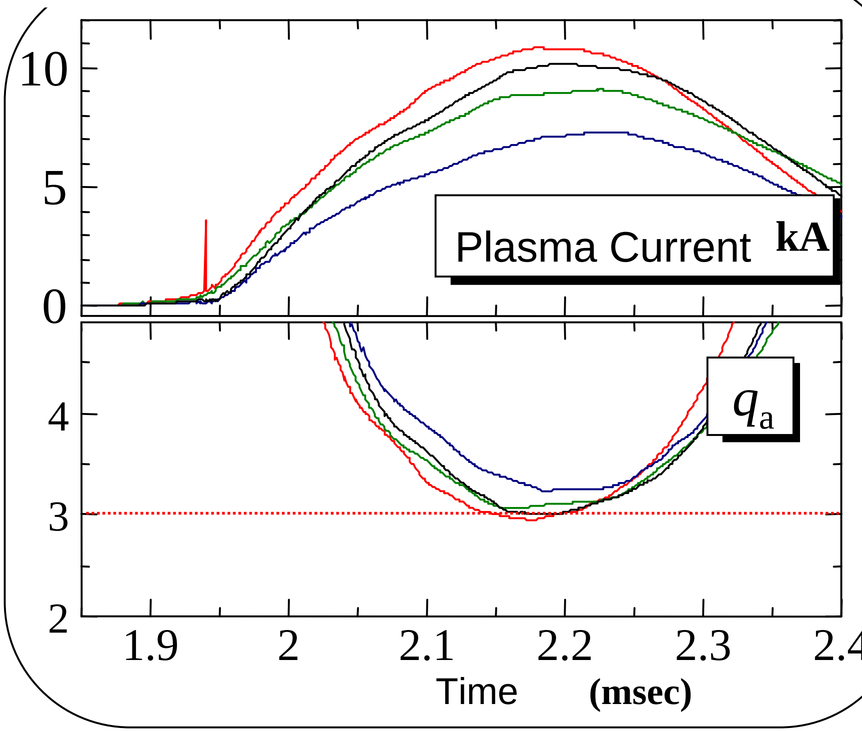


Maximum current is enhanced to about 1.6 times.

Peak plasma current



Plasma current and safety factor



Safety factor on plasma surface

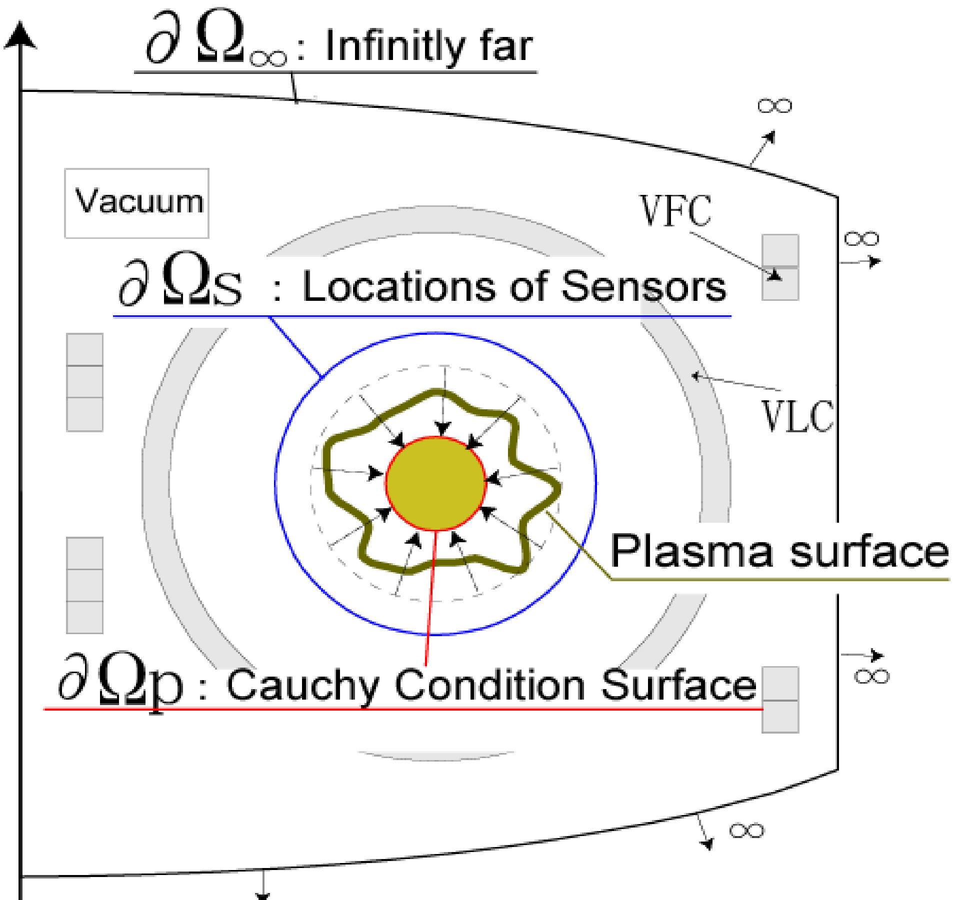
$$q_a = \frac{aB_T}{R_0 B_P} \cong \frac{2\pi a^2 B_T}{\mu_0 R_0 I_P} \geq 3$$

R_0 : Major radius

Cauchy Condition Surface (CCS) method

CCS method is based on an exact integral equation.

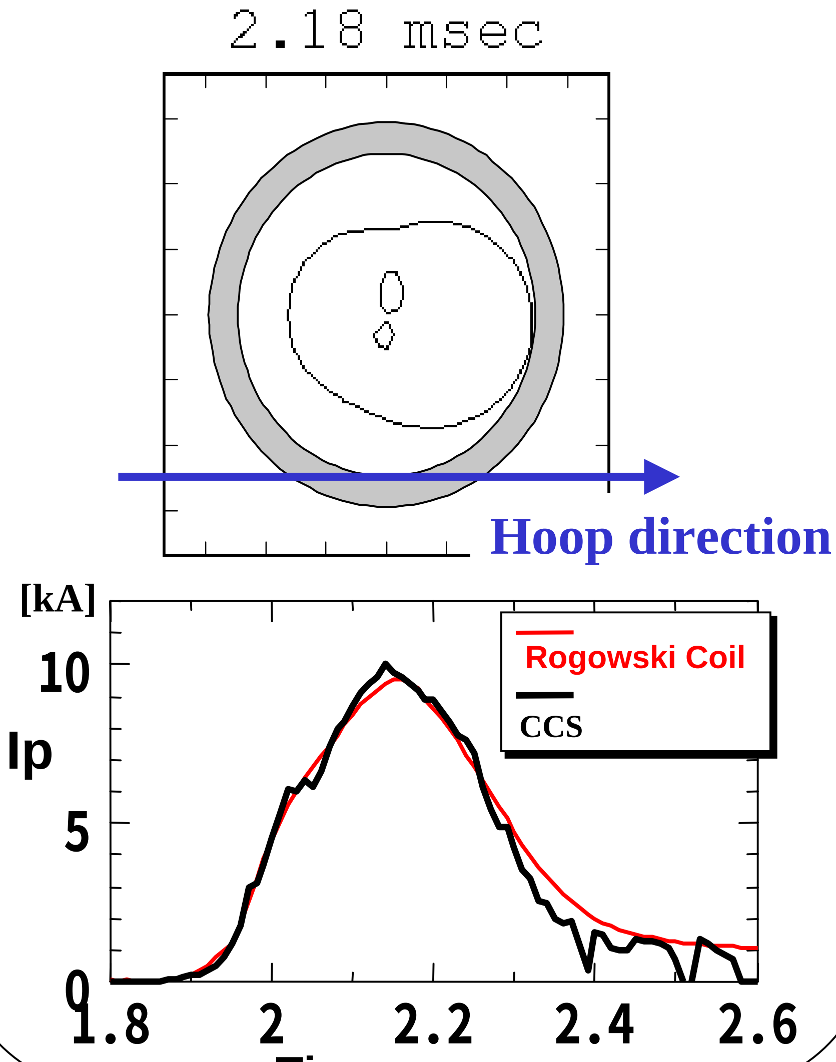
$$\sigma \cdot \phi(x) + \int_{\partial\Omega_P} [G(x,y)grad\phi - \phi(y)gradG]dS/r_y = \int_{\Omega_P} \mu_0 j_c(y)G(x,y)dV(y)/r_y^2$$



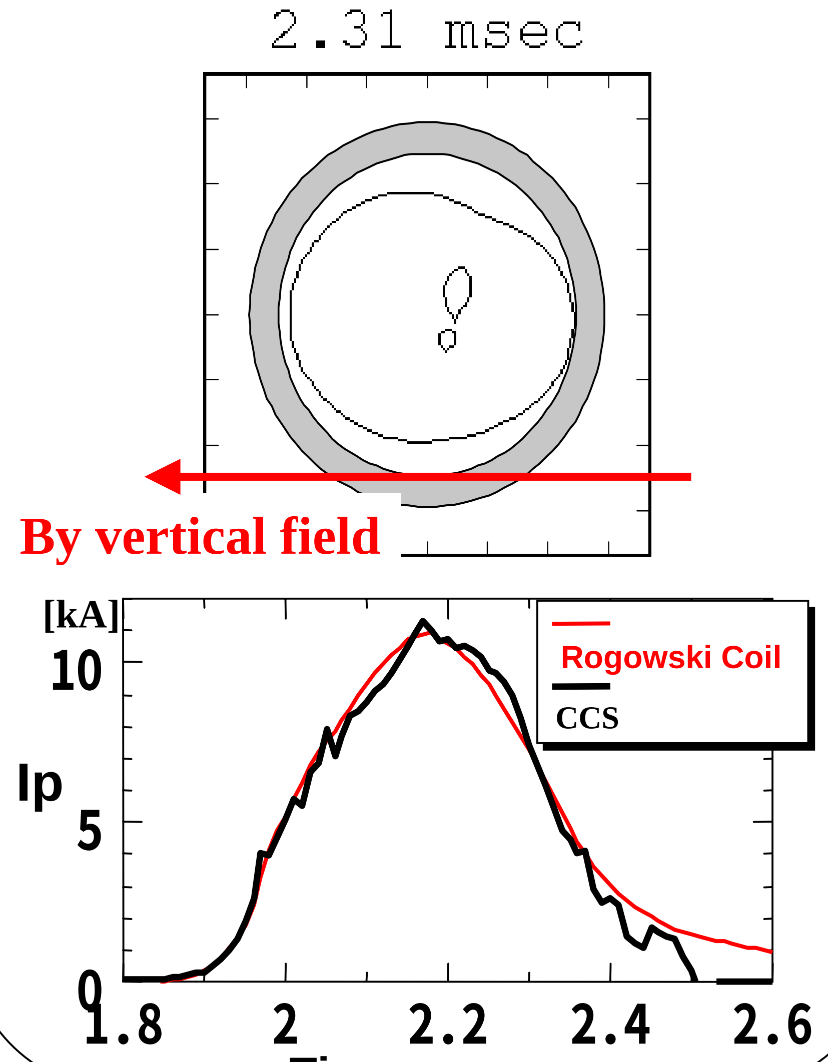
- **Magnetic field by plasma current is replaced by surface integrals of B and ϕ on CCS.**
- **B and ϕ on CCS are determined from sensor signals.**
- **Accuracy of calculation increases with the number of sensor signals.**
- **Axisymmetry is assumed.**
- **Plasma current is also evaluated from magnetic data.**

Visualization by CCS

Without vertical field



With vertical field



Summary I

- The relation of toroidal field and stress is obtained by **virial theorem**, which shows that the optimal stress configuration is uniform tensile stress.
- When *A*=2, VLC makes 1.4 times stronger magnetic field than TF coil.
- **VLC** winding generates small error fields, and makes room for blanket and other parts in conventional tokamak reactors.
- Nearly uniform stress distribution with **VLC** configuration is obtained from both uniaxial model and FEM analysis.
- A small **VLC** tokamak ***Todoroki-II*** was constructed and its experiments started.

Summary II

- Peak plasma current with an additional vertical field was increased to 1.6 times larger than that of non-vertical field discharge.
- Error field is estimated from eddy current by FEM.
- It was shown that plasma current was limited by loop voltage or toroidal field strength.
- Plasma current and surface were evaluated by **CCS** method, and validity of **CCS** method for a small pulsed tokamak was verified.
- In order to increase discharge time, current control with arbitrary wave form is required.