magnetosphere-like plasma experiment (RT-1 project)

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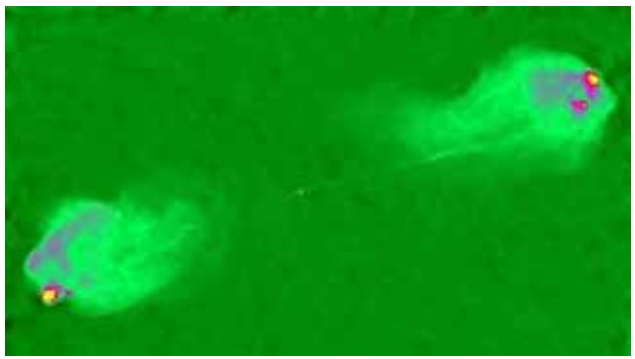
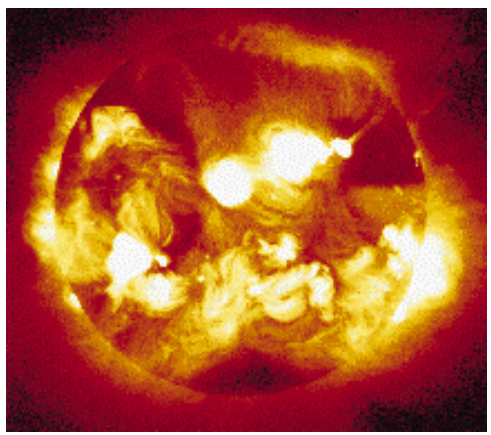
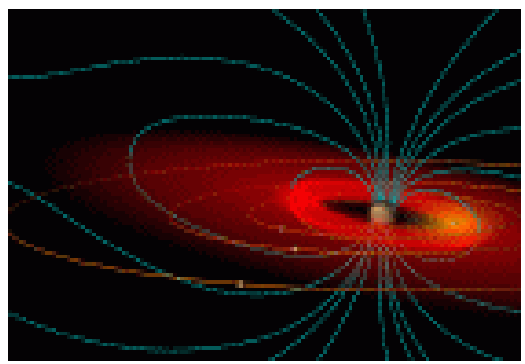
A Frontier of Plasma Physics

Interesting "structures" remain unknown in the universe.

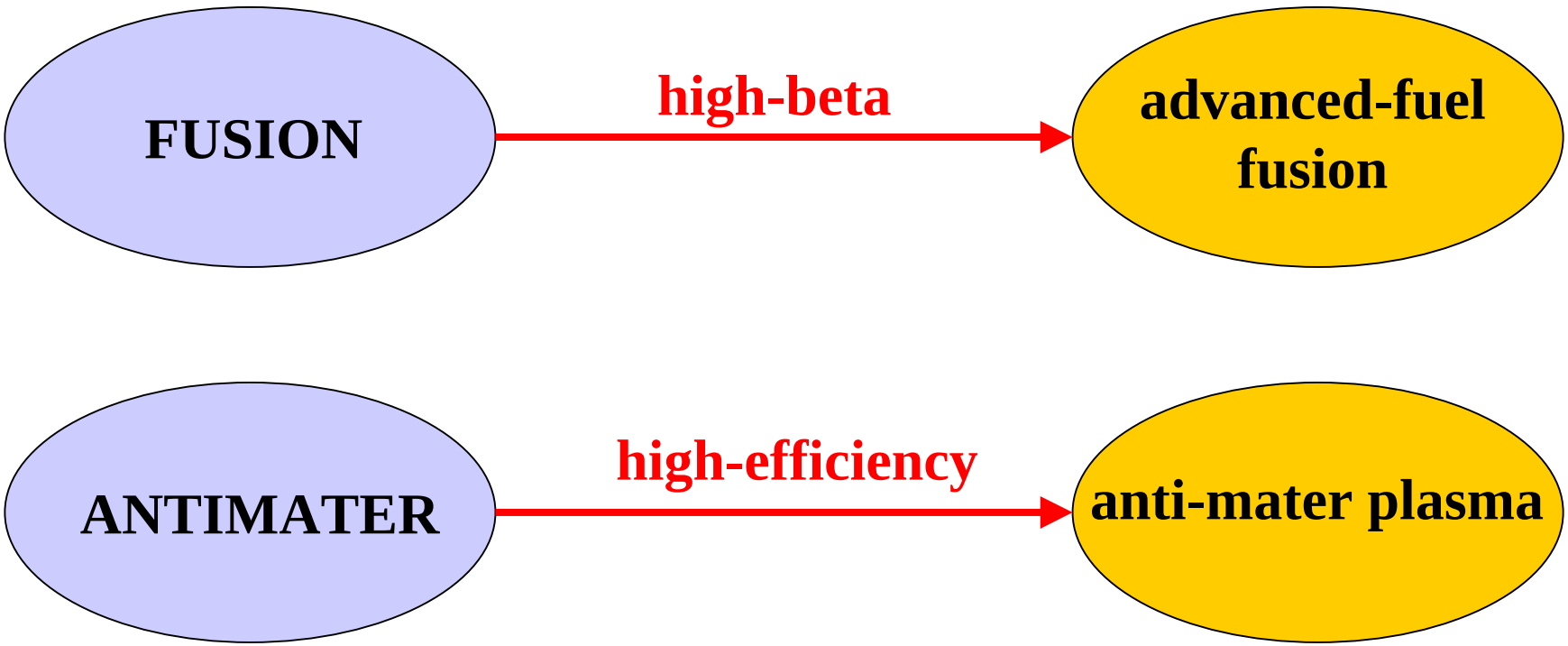






A Frontier of Plasma Physics

Interesting "structures" remain unknown in the universe.



Guidelines to analyze/synthesize plasma structures

- How can plasmas have “diversity” of structures?
  - compared with a linear system (ex. heat diffusion eq.)
  - nonlinearity → bifurcation
  - hyperbolicity, singularity (non-canonical nature) → characteristics

- What is the measure of plasma’s “preference” ?
  - target functional → variational principle
  - conservation laws, Casimirs → constraints

- How can we organize a preferable structure?
  - relaxation → self-organization

Self-Organization of Structures

- **Relaxation**
  a natural process of chaos
  escape from restrictions → homogenize

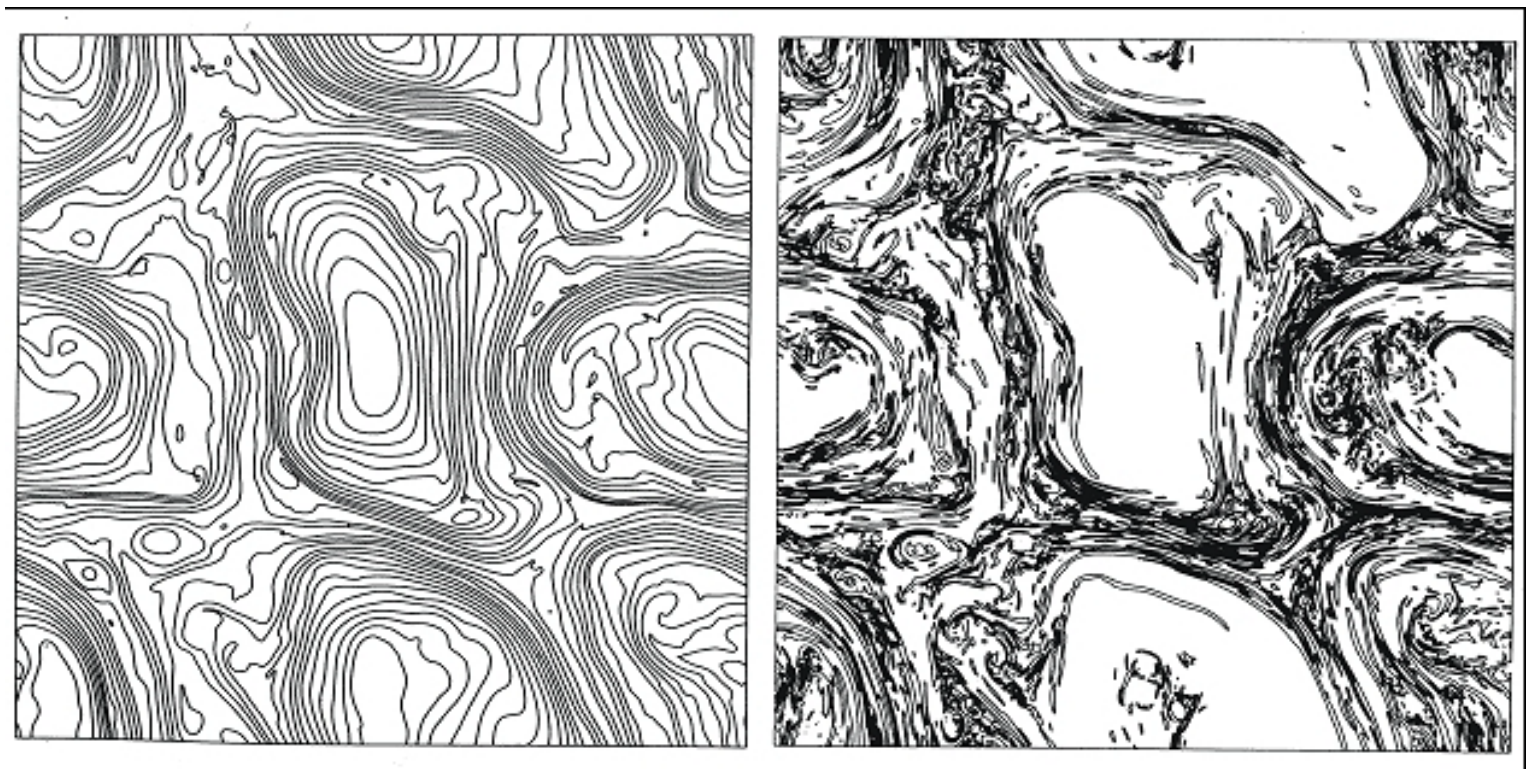
- **How can "structures" emerge and sustain?**
  co-existence of order and disorder
  ← creation of scale hierarchy (multi-scale)

- **Order ← "symmetry" (conservation laws):**
  diversity of structures, stability (Lyapunov functions)

- **Dynamic (non-conservative) degree of freedom:**
  entropy vs. dynamics

Plasma = co-existence of order and disorder

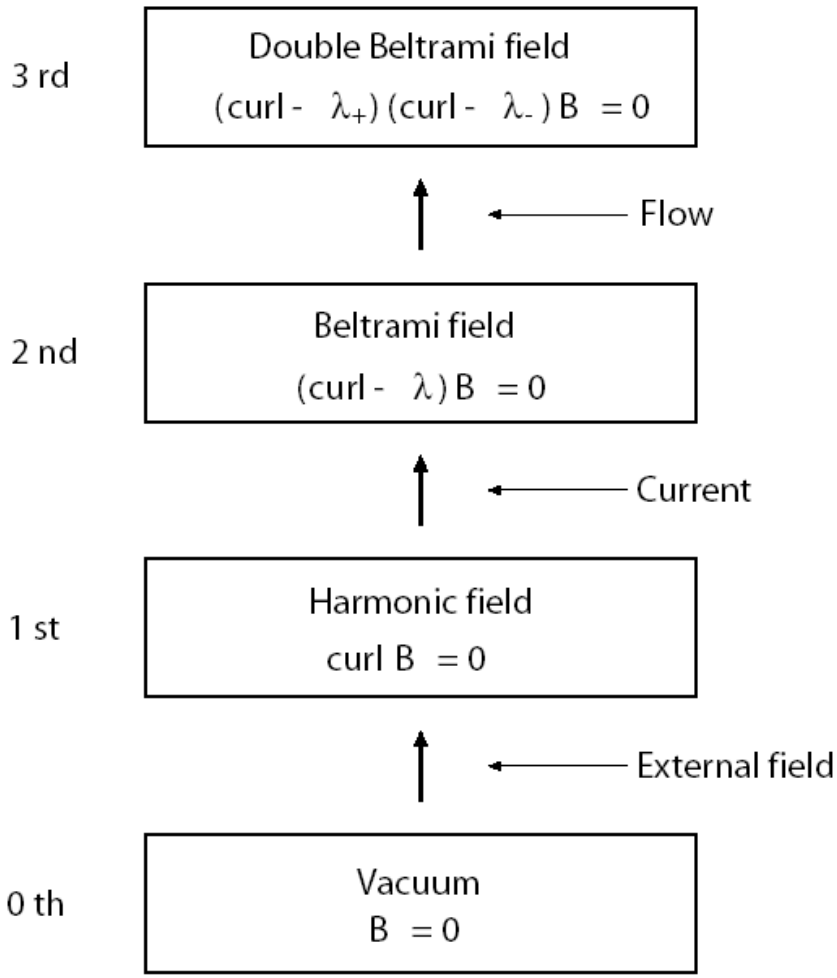
- Interactions of different scale hierarchy
- Analysis of singularities (singular perturbation theory)



macro micro

by Biskamp

Flow-field coupling



Self-organization of "twists"

S.M. Mahajan and Z.Yoshida, Phys. Rev. Lett. **81** (1998) 4863.
Z. Yoshida and S.M. Mahajan, Phys. Rev. Lett. **88** (2002) 095001.

Symmetry and diversity

- **equilibrium = critical point of the "Hamiltonian"**

  $\delta H = 0 \rightarrow$ "trivial state"

- **Non-Canonical system : Casimir invariants (constant of motion) → restriction**

  $\{C, G\} = 0$ (for every G)

- **Non-trivial (structured) equilibrium**

  $H' = H + \mu C + \mu' C' + \cdots$

  $\underline{\delta H' = 0} \rightarrow$ "non-trivial states"

  $H' \rightarrow$ Lyapunov function

Z. Yoshida, S. Ohsaki, A. Ito and S.M. Mahajan, J. Math. Phys. **44** (2003) 2168.

"Beltrami"-class of equilibria

- **Vortex dynamics system:**

$$\partial_t \boldsymbol{w}_n - \nabla \times \left(\boldsymbol{v}_n \times \boldsymbol{w}_n \right) = 0 \quad \left(n = 1, 2, \cdots \right)$$

- **Casimirs = Helicities → topological constraints**

$$C_n = \int \boldsymbol{w}_n \cdot \nabla^{-1} \times \left(\boldsymbol{w}_n \right) dx$$

- **Structured equiliria:**

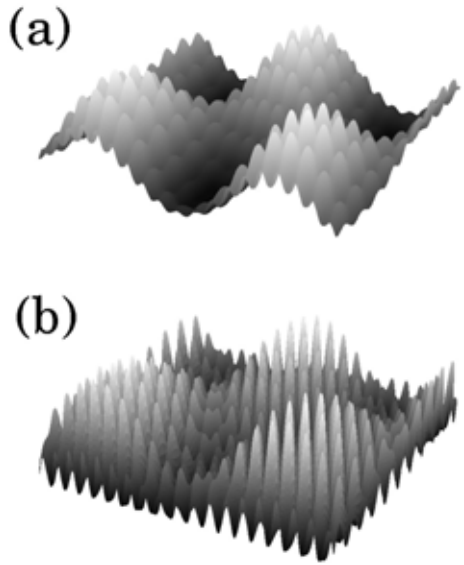
$$\delta F(\boldsymbol{u}) = \delta \left(H(\boldsymbol{u}) + \sum \alpha_j C_j(\boldsymbol{u}) \right) = 0$$

- **Beltrami vortex solutions**

$$\left(\mathrm{curl} - \lambda_1 \right) \cdots \left(\mathrm{curl} - \lambda_N \right) \boldsymbol{u} = 0$$

Z. Yoshida and Y. Giga, Math. Z. **204** (1990), 235-245.
Z. Yoshida and S,M, Mahajan, J. Math. Phys. **40** (1999), 5080.

Double Beltrami field in HMHD plasma



$$\boldsymbol{u} = c_1\boldsymbol{G}_1 + c_2\boldsymbol{G}_2$$

$$\mathrm{curl}\,\boldsymbol{u} = c_1\lambda_1\boldsymbol{G}_1 + c_2\lambda_2\boldsymbol{G}_2$$

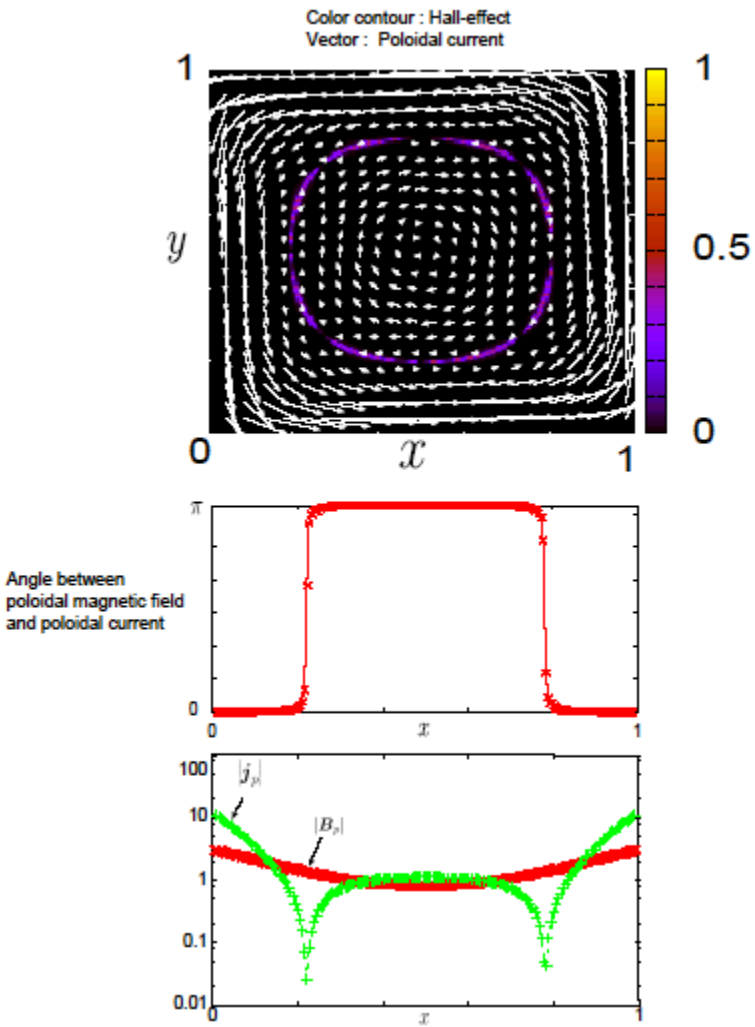
$$\lambda_1 = O(1), \quad \lambda_2 = O(\varepsilon^{-1})$$

← **multi-scale**

Z. Yoshida, S.M. Mahajan, S. Ohsaki, Phys. Plasmas **11** (2004), 3660.

Singular perturbation healing singularities

- **The Alfven singularity is unfolded by the Hall effect:**



ideal limit ($\varepsilon \to 0$) :

order parameter $$f = \frac{\boldsymbol{v}\cdot\boldsymbol{B}}{|\boldsymbol{v}|\cdot|\boldsymbol{B}|} = \pm 1$$

Hall effect (singular perturbation)

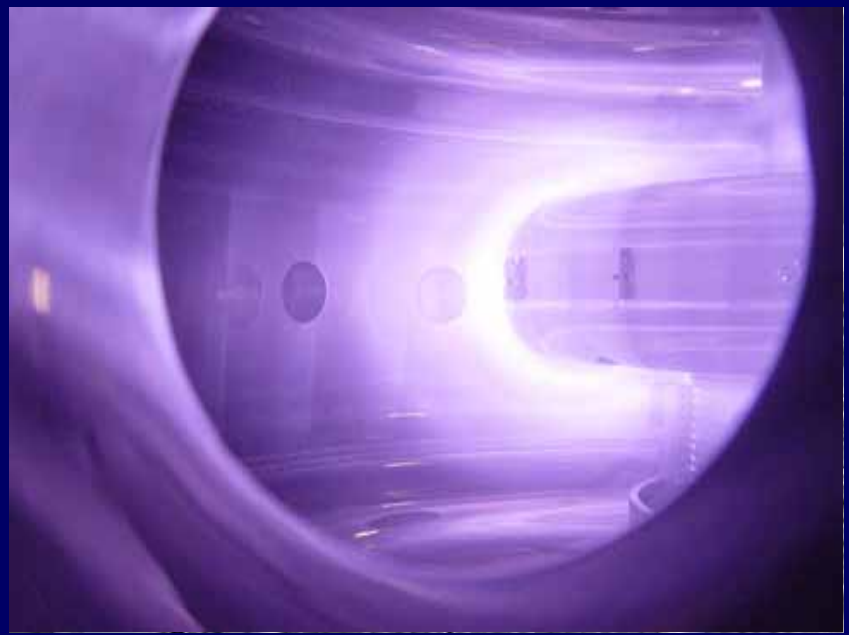
smoothly connect two different phases:

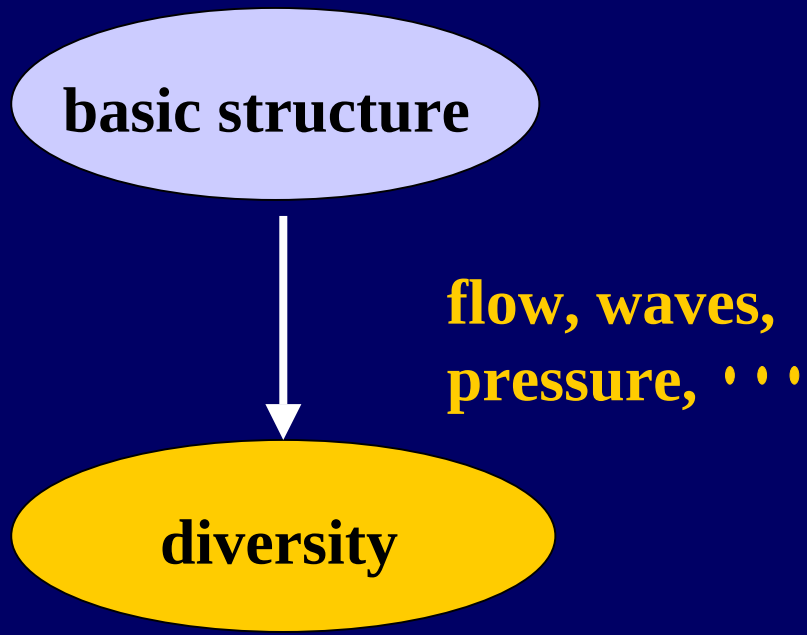
$$-1 \le f \le +1$$

J. Shiraishi, S. Ohsaki, Z. Yoshida,
Phys. Plasmas **12** (2005), 092308.

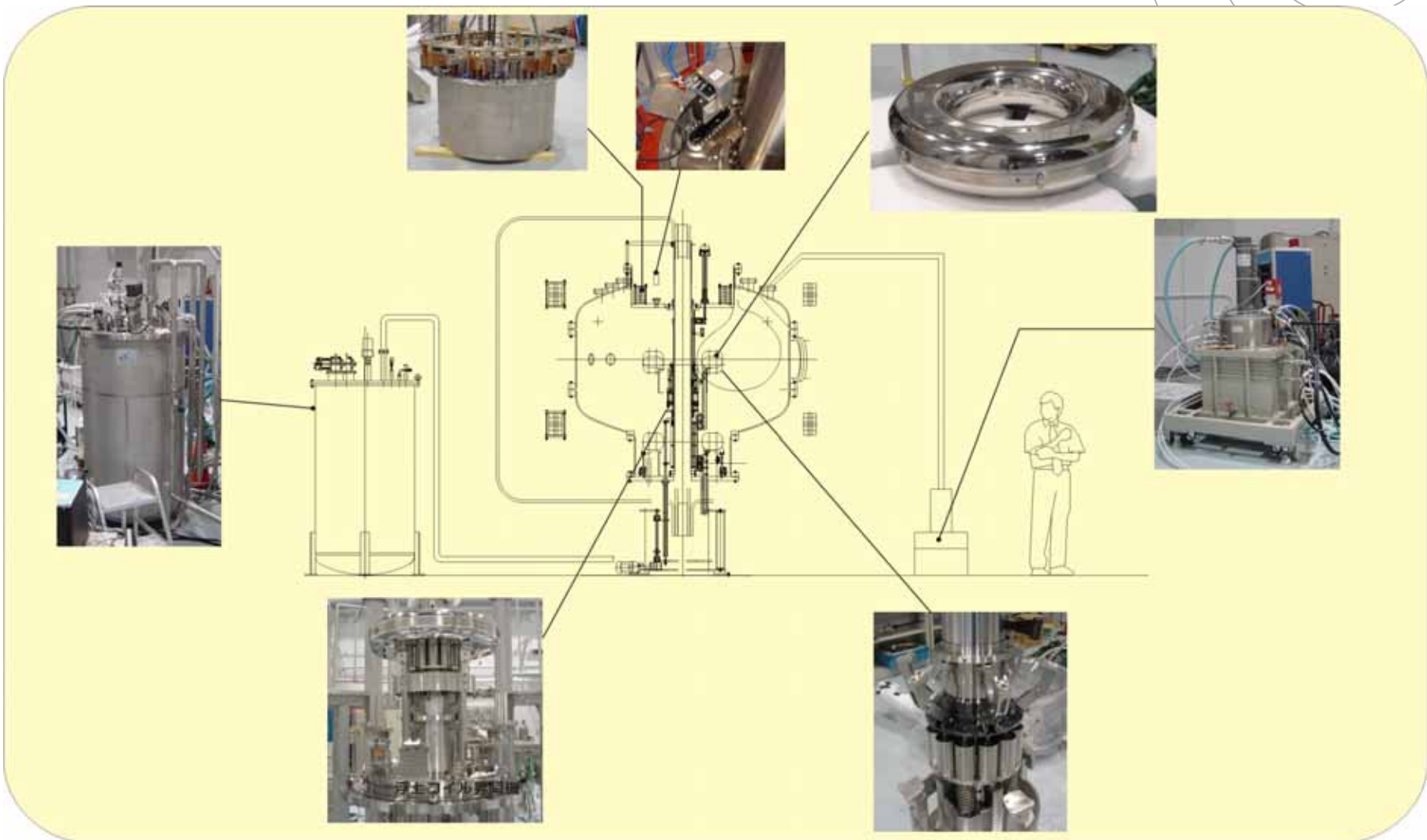
RT-1 device

Magnetosphere-like plasma confinement





RT1 engineering



Challenges using RT1

- Advanced-fuel fusion
  - high-beta confinement
- New method of trapping particles
  - magnetic-surface configuration
- Plasma-astrophysics
  - experimental simulation of magnetosphere
- Basic plasma physics
  - flow, relaxed state, wave propagation,
  - particle-orbit (neo-classical) effects,
  - boundary layer, shocks and singularities, etc.

Summary

- **The RT1 device: magnetosphere-like configuration**

  high-temperature super-conducting magnet

- **RT1 can host a variety of new-type plasma states.**

  high-beta rotating plasma (Jupiter's magnetosphere)

  Double Beltrami states (Hall-MHD), dipole (mirror-like),

  non-neutral (single-species) plasma, ' ' '

- **Flow-field coupling produces diverse structures.**

  multi-scale structures, singular perturbations,

  topological constraints, Lyapunov stability, ' ' '