Maintenance Concept for Modular Blankets in Compact Stellarator Power Plants

Siegfried Malang

With contributions of
Laila A. EL-Guebaly
Xueren Wang

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Overview of maintenance concepts in previous Stellarator studies:

- No scheduled replacement of blankets (FFHR-Study, 450 dpa in FW allowed)

- Disassembling of the modular coil system for blanket replacement (SPPS-Study)

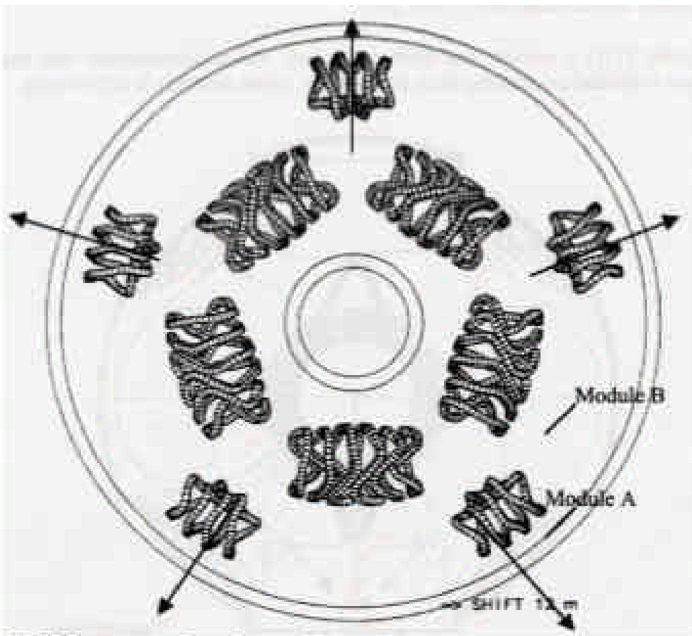
- Arrangement of maintenance ports between all modular coils (HSR-Study)

- Maintenance of blanket modules with an articulated boom, inserted through a small number of maintenance ports (this presentation)

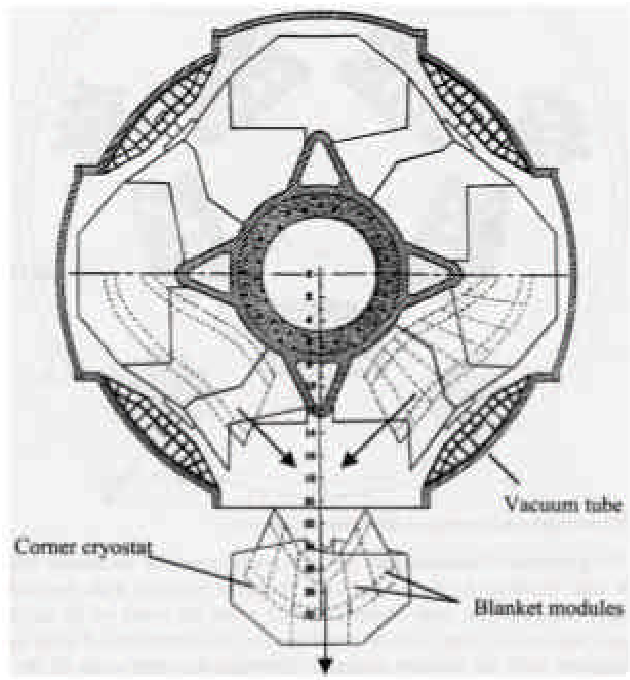
Alternate Maintenance Concept

- Radial/toroidal movement of large modules

ASRA6C

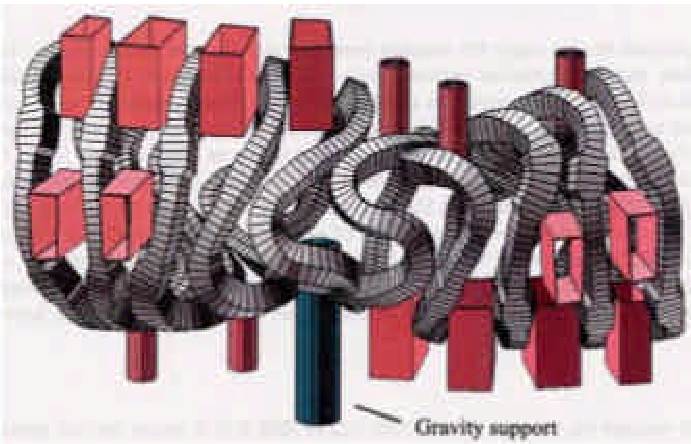


SPPS

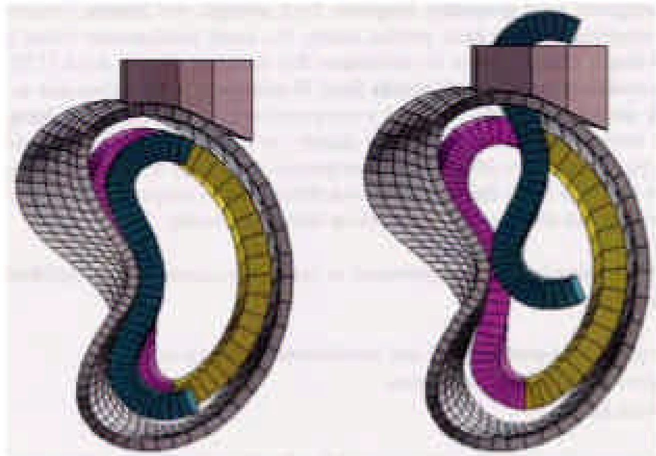


HSR Maintenance Concept

- HSR5/22: small modules thru ports



One field period of the coil system with ports



Maintenance scheme for blanket segments

Main issues in selecting blanket concepts for maintenance with an articulated boom:

A) Space between FW and VV very restricted at some locations

B) Relatively high thermal efficiency of the power conversion system is mandatory for attractive plant

C) Cutting and re-welding of coolant access tubes must be possible with in-bore tools, inserted from the plasma region

D) Number and geometry of tubes to be cutted and re-welded is important for down-time and reliability

E) Load capacity of boom limited to ~ 3 tons
→ as higher the specific weight of blanket modul, as smaller the allowable module size

Candidate blanket concepts:

a) Self-cooled liquid metal blankets

- **Very attractive with Pb-17Li and SiC-composites, but crucial issues of SiC-composites to be solved**
- **With steel feasible only with insulating coatings between flowing liquid metal and walls**
- **Relatively heavy structure with Pb-17 Li**
- **Relatively thick blanket + shield required with Li**

b) Water-cooled Pb-17Li blanket

- **Thermal efficiency of blanket system < 35 %,**
- **Pressurisation of blanket in case of a LOCA is safety concern**
- **Heavy blanket structure required**

c) Helium cooled blankets, either with liquid metal breeder or with ceramic breeder

- **Large helium cooling channels and manifolds require relatively thick blankets + shield**
- **High gas pressure leads to heavy structure**
- **Relatively low achievable coolant exit temperature limits thermal efficiency**

d) Blanket concept based on FLiBe and advanced ferritic steel (this presentation)

Why do we select a FLiBe/ Steel blanket concept as an example?

F) FLiBe can be used as breeder and coolant
→ self-cooled blanket enables simple geometry and high exit temperature

G) Electrical conductivity of FLiBe low enough to avoid need for insulating coatings

H) Thinner breeding zones are required for tritium self-sufficiency and shielding compared to other breeder materials
→ 30 cm breeding zone sufficient to make the zone behind to a life-time component

I) Low pressure minimizes the weight of structure

J) Only one concentric tube required as coolant access tube for each module

K) FLiBe can be used as shield coolant without the need for an additional neutron moderator

Challenges for the design of FliBe-Blankets:

a) **Exceptional low thermal conductivity of FliBe**
(1 W/(m*K) compared to 15 W/(m*K) for Pb-17Li and 50 W/(m*K) for Li)
To obtain sufficiently large heat transfer, high turbulence is required.

b) **Viscosity of FliBe is really high, especially at temperatures close to the melting point.**
(At 500°C for example, the kinematic viscosity is 11.5 E-6 m²/s compared to 0.12 E-6 m²/s for water at 300°C, 15 MPa (PWR-conditions)
High velocities and/or large channel dimensions are required to obtain sufficient turbulence.

c) **Breeding capabilities of FLiBe are limited, making additional neutron multiplier mandatory. Usually a region of beryllium with a thickness of 3-5 cm is arranged close to the first wall (FW). This implies the problem of beryllium swelling under neutron irradiation (10-15 vol.% at end-of-life conditions), and a large tritium inventory in the beryllium (up to some kg's) which is a safety concern.**

d) **The high melting point of FLiBe (459°C for $(LiF)_2(BeF_2)$) requires a structural material with a temperature range up to > 650°C. In addition, FliBe is rather aggressive to a number of candidate structural materials. This requires an excess of beryllium in contact with the FLiBe in order to stabilize the fluor in the salt. This contact can be provided either inside the blanket or outside the irradiation environment.**

Selected structural material, given temperature limits, and assumed coolant conditions :

- In order to have a sufficiently large temperature window, advanced ferritic steels (Nano Composite Ferrites, “NCF”) are selected.

- Temperature limits for NCF, given by the US materials community:
  a) Max. steel temperature < 800 C
  b) FLiBe/steel interface < 700 C

- FLiBe temperatures at
  a) blanket inlet 550 C
  b) blanket exit 700 C

- Helium temperatures in power conversion system (Brayton cycle with two turbine stages):
  a) HX outlet 670 C
  b) HX intlet 520 C

- Achievable thermal efficiency > 45%

Characteristics of the selected modular blanket concept:

A) Replacement units are composed of FW and breeding zone only, no additional shielding required to make the region behind to lifetime components.

A) First wall surface area of a module typically 2mx2m, resulting in a total weight of less than 1,500 kg for a 0.3m deep breeding zone.

B) One concentric coolant access tube per module with the “cold” inlet flow in the annulus and the “hot” outlet flow in the centre tube.

C) Only the outer access tube has to be cut/re-welded for blanket replacement. Sliding seals are used for the inner tube, because small leaks between inlet and outlet FLiBe flow have no impact.

Characteristics of the selected modular blanket concept (continued):

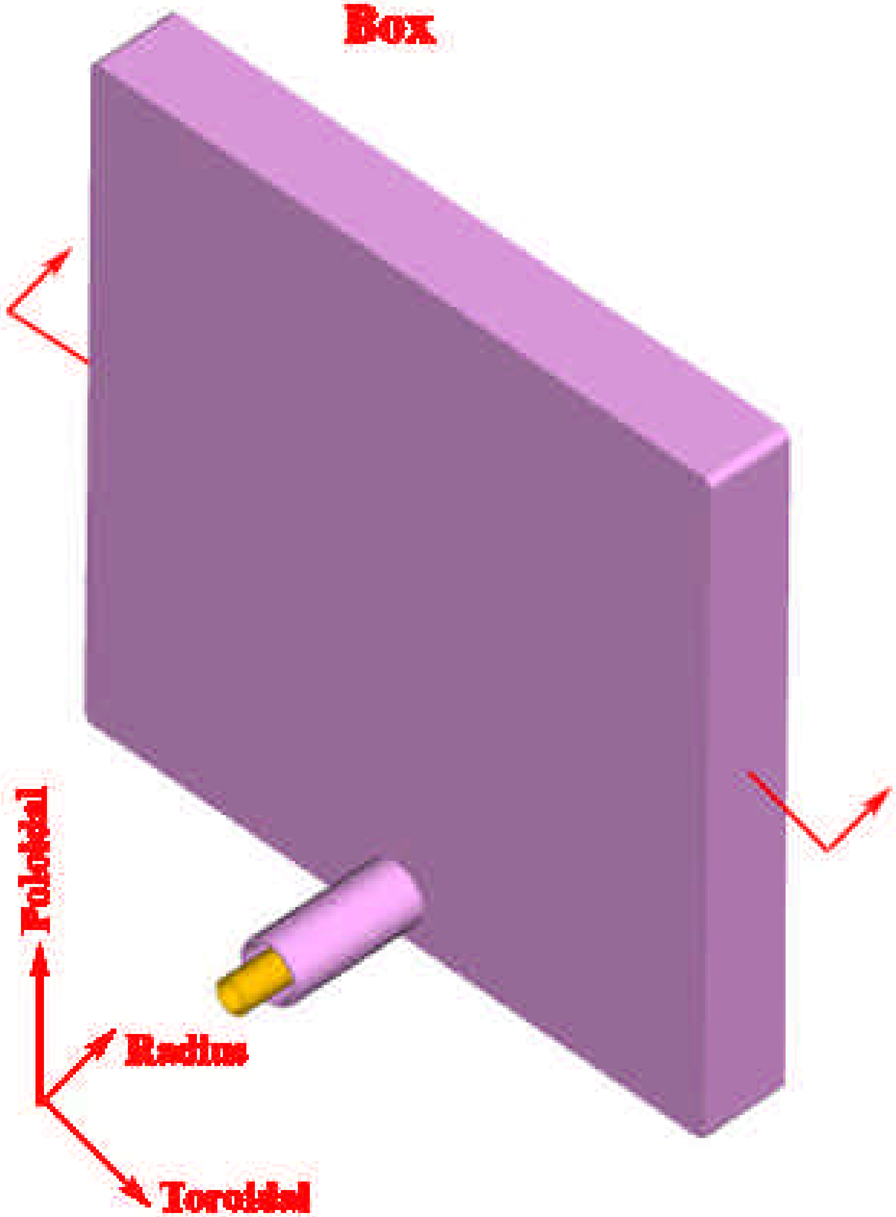
D) Cold inlet flow cools the entire structure. The slowly flowing FLiBe in the large central ducts is heated up by the volumetric heat generation to a temperature equal or higher than the maximum interface temperature.

E) Arrangement of a few cm thick beryllium pebble bed between perforated plates in the FW region, serving both as neutron multiplier and for chemistry control of FLiBe which is flowing with very low velocity through the pebble bed.

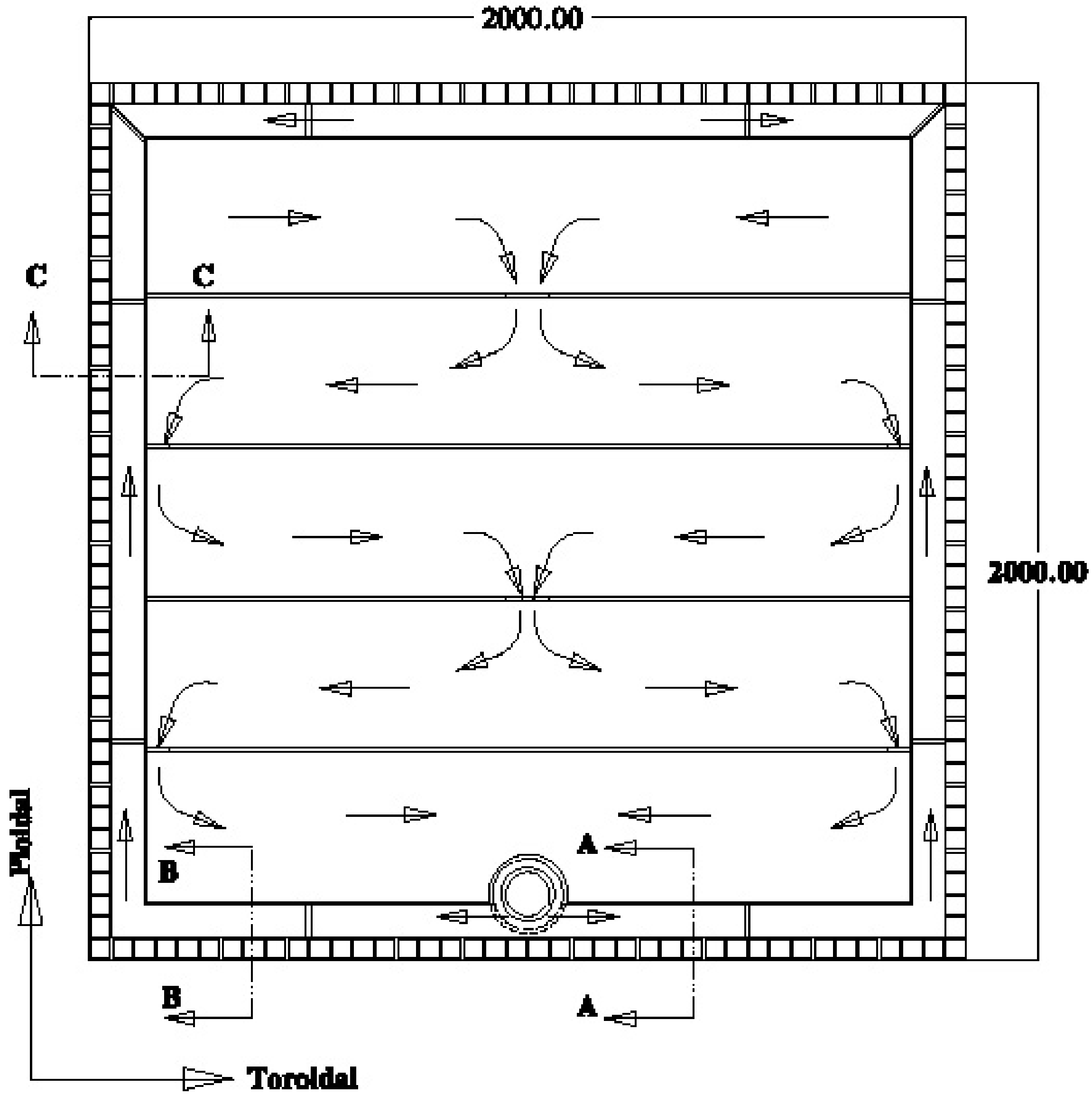
F) Maximum pressure in the FLiBe < 0.5 MPa, allowing low steel fraction (~5 %) in the breeding zone.

G) Maximum NWL up to 5 MW/m² feasible with the concept.

Isometric View of the Flibe Blanket Box

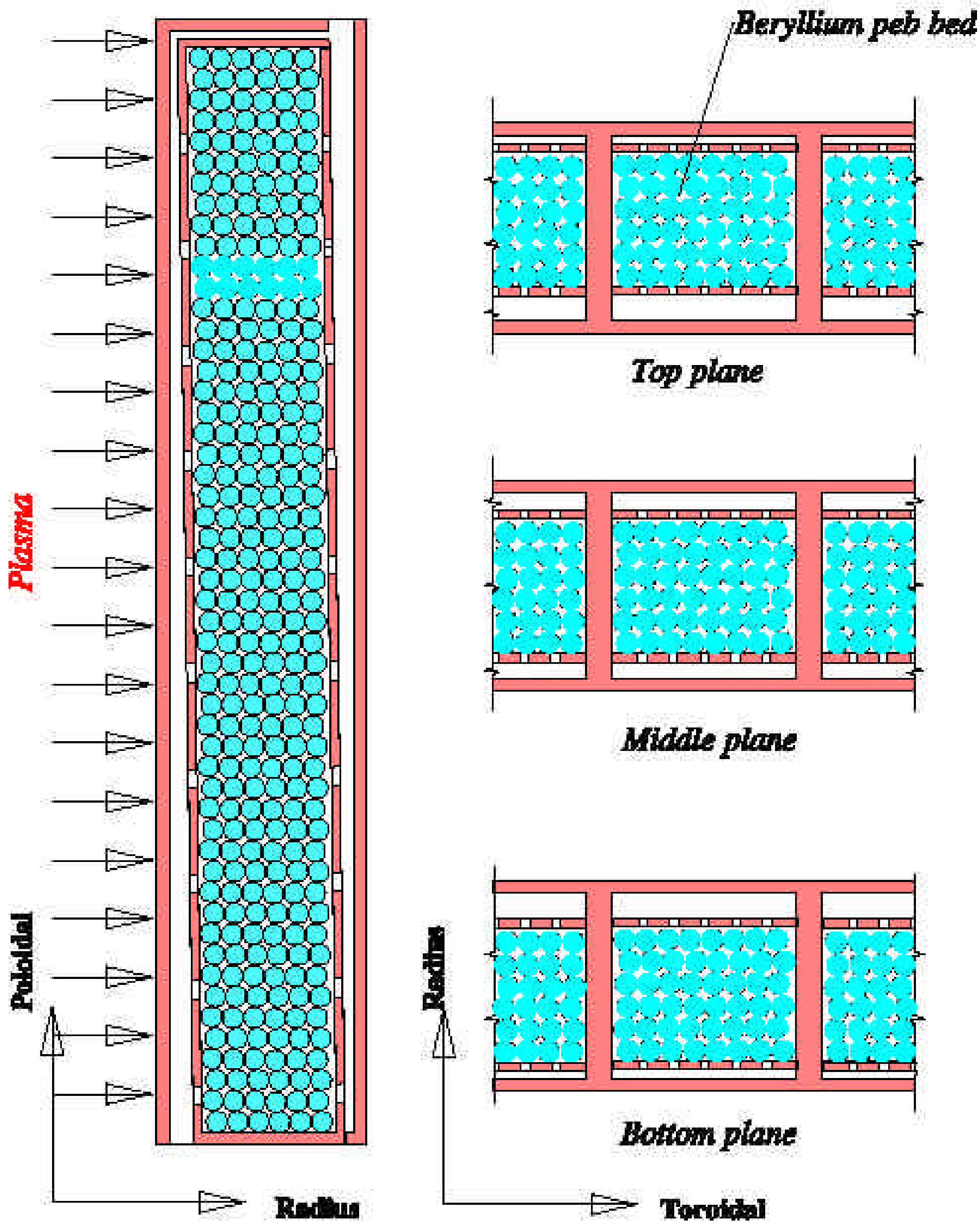


Cross-section of the Flibe Blanket Box
(View From Back Side)

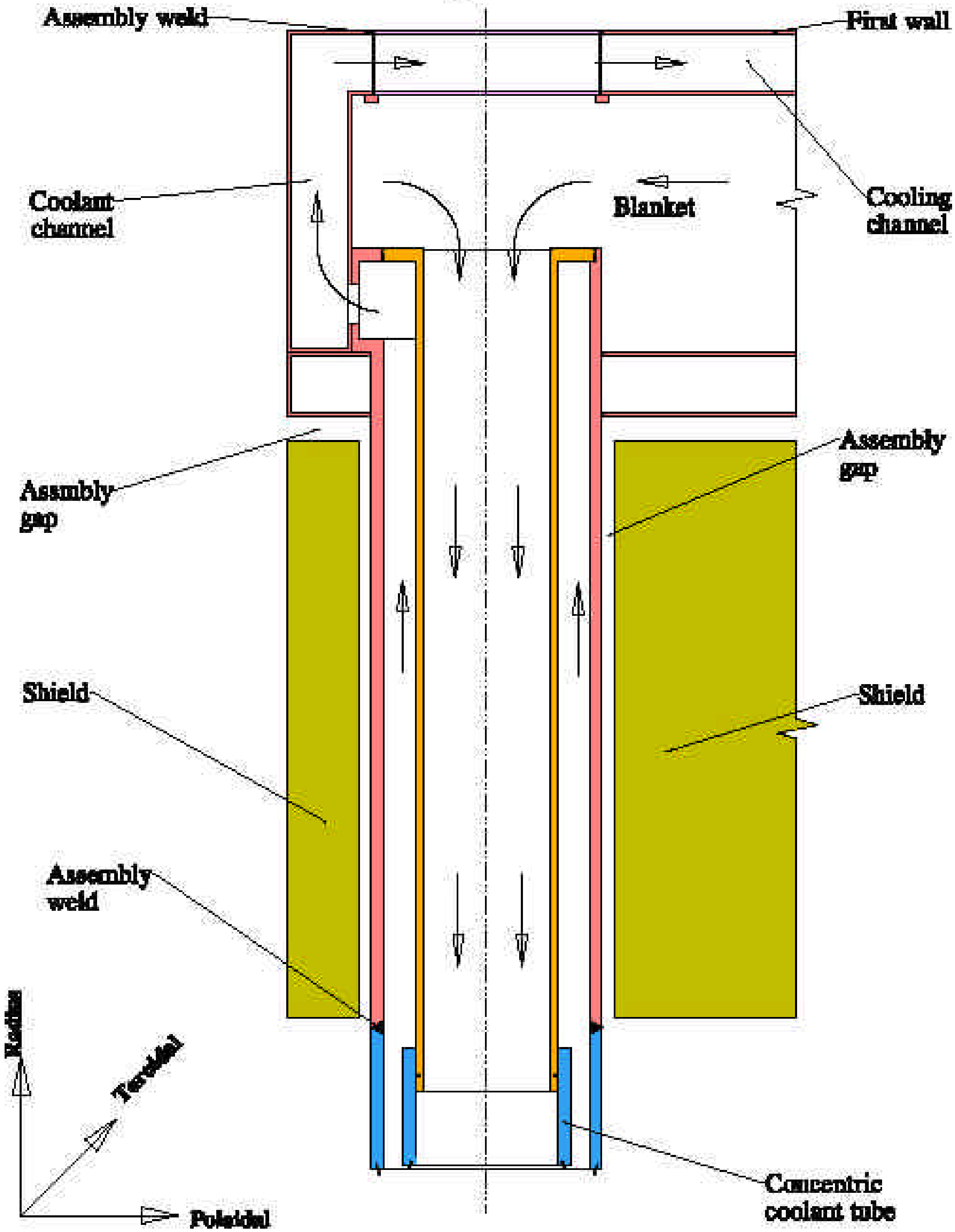


Cross-section Showing First Wall and Multiplier Region

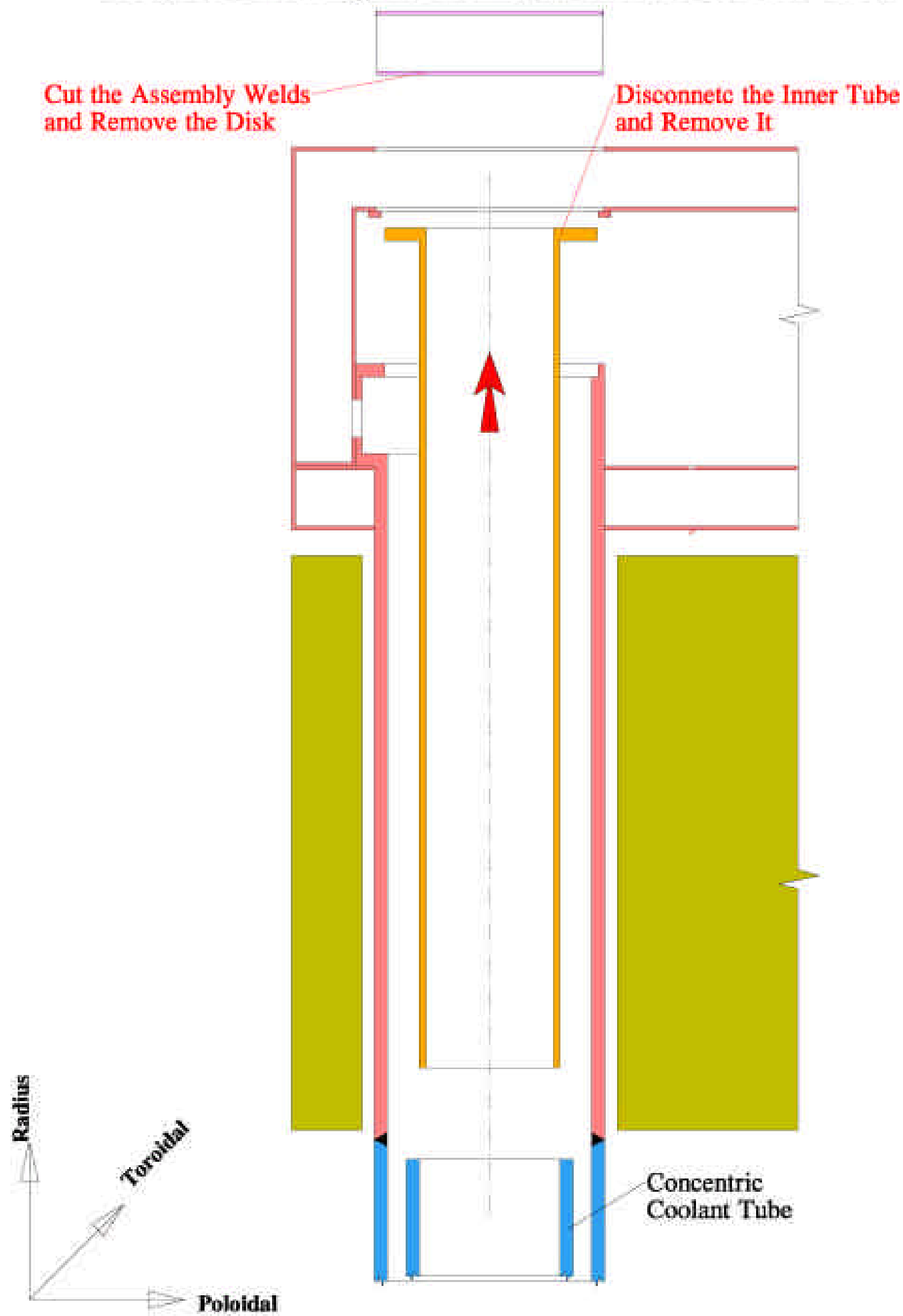
(Schematic)



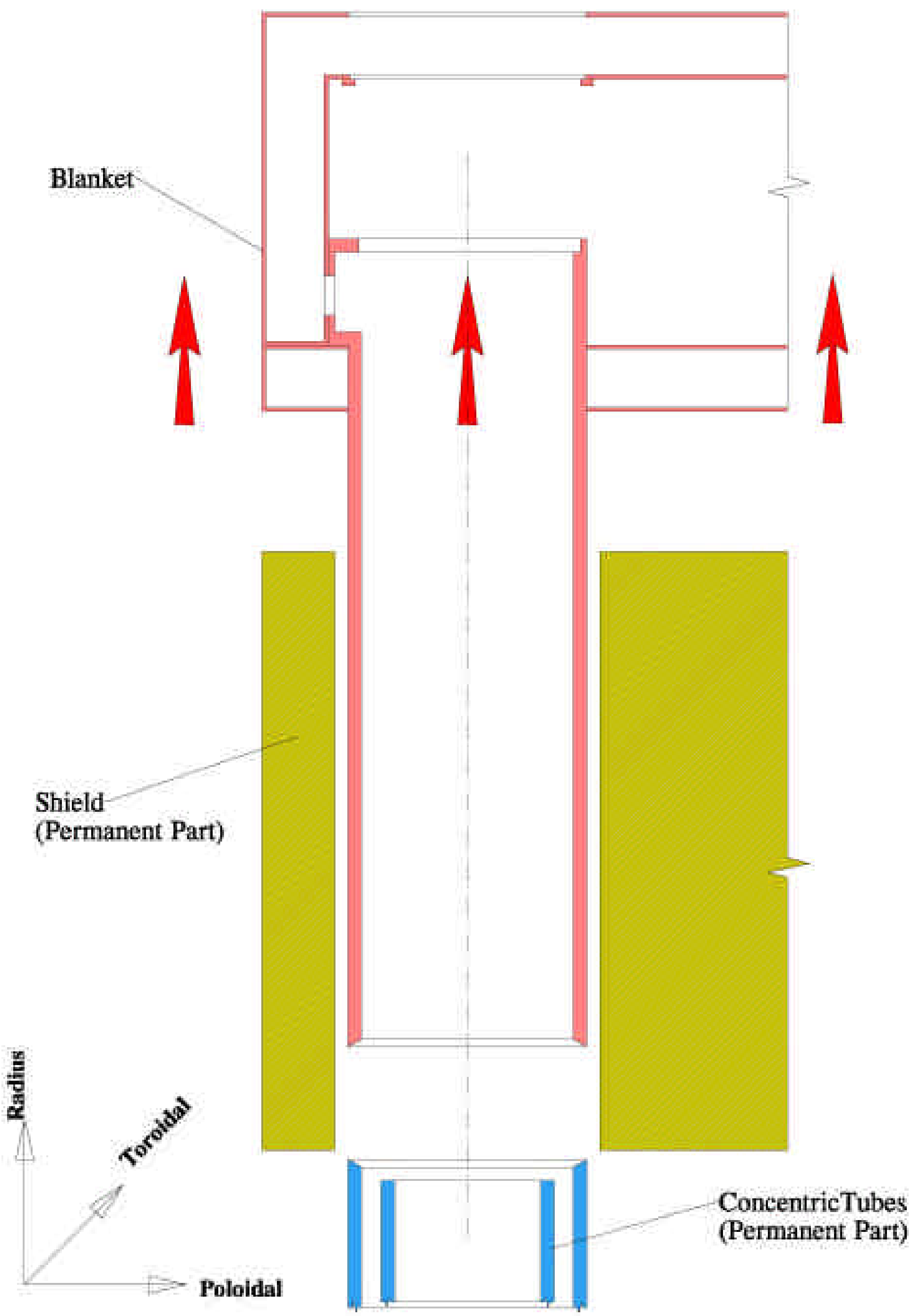
Cross-section Showing the Access Coolant Tube



Steps of Showing the Removal Access Coolant Tube



Steps of Showing the Removal Blanket Box



Summary and Conclusions:

A) Blanket replacement possible with articulated booms, inserted through a small number of maintenance ports (for example one horizontal port in each magnet period).

B) Blanket concept based on FLiBe as breeder/coolant and advanced ferritic steel as structural material especially suited for this maintenance method because:
   - low weight of replacement unit,
   - thin breeding zone required for tritium self-sufficiency and sufficient shielding to make region behind to life-time component,
   - volumetric heating in FLiBe allows to achieve coolant exit temperature higher than interface temperature,
   - temperature window sufficiently large for high efficiency BRAYTON cycle power conversion system.

C) Maintenance boom can be used additionally for the replacement of high power divertor target plates. The arrangement of such plates is facilitated by the modular blanket concept.

Proposed next steps for the maintenance concept based on articulated booms:

1. Make conceptual designs and scoping analyses of the following alternative blanket concepts for the same application and assuming the same boundary conditions as used for the FLiBe/Steel concept:

   a) Self-cooled Pb-17Li blanket with SiC-composite as structural material (ARIES-AT)
   b) Self-cooled Pb-17Li blanket concept with He-cooled steel structure and SiC flow channel inserts (ARIES-ST),
   c) He-cooled Pb-17Li blanket concept with steel structure (European DEMO blanket).

   In all three cases, the required thickness for tritium self-sufficiency and sufficient shielding of the region behind the replacement unit has to be determined.

2. Get information about realistic sizes of maintenance ports in a compact Stellarator power plant.

3. Get estimates about realistic load capacity of articulated booms for the port dimensions anticipated.

4. Determine the maximum allowable module size for the alternative blanket concepts.