NCSX Requirements

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Objectives

- Review "working" requirements
- Identify potential design impacts
- Discuss mitigation possibilities
- Get feedback

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Topics

- Operational requirements
- Siting in PBX
- Reference design scenario
- HF coil assembly design
- TF/PF coil design modifications
- VV and PFC design
- Auxiliary heating
- Cost & schedule

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Operational requirements

Cooldown/warmup time	1	week	
Maximum pulse repetition time	5 (10)	min	Goal (maximum); indirect cooling makes short cooldown times difficult
Design life	10	years	
Maximum number of pulses			When operated per reference operating scenario
	100		Per day
	13000		Per year
	130000		Lifetime
Fuel	H, D		
Shielding	None		D operation administratively limited to avoid the need for additional biological shielding

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Assume NCSX is sited in PBX

- Option 2c
- PBX disassembled down to base
  - *Pin removal results were very positive*
- Design stellarator core installed as a pre-assembled module
  - Pre-assembled in PLT area
  - Test cell crane capacity is 30 tons
    - *limits mass of stellarator core*
  - Re-assembly of PF and TF follows installation of core
- PBX equipment re-used where cost-effective
  - TF and ex-vessel PF coils (*except OH solenoid?*)
  - *VV modified for use as a cryostat?*

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Impacts of PBX siting

- Limits plasma aspect ratio to high end (>3.4)
- 3 period plasmas have symmetry conflicts with TF (20 fold) and torque structure (5 fold)
- Requires close-fitting HF coils, even on the outboard side
- Space limitations allow
  - only one coil layer (?)
  - limited space for HF coil leads
  - limited space for shape flexibility
- Maintainability of cold mass is very poor due to access limitations

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Final plasma configuration not yet selected

- c10 will continue to be the basis for near-term engineering studies
- Not a candidate for the "final" configuration because of kink stability
- c82 (a kink stable derivative of c10) not attractive because of coil current density (order 25 kA/cm^2 at 1T, twice c10)
- Alternatives to c10 and c82 being sought
  - Lower central iota, higher aspect ratio, alternatives derived by suppressing J_s ...
  - Coil design is a major consideration in development of alternatives
- Target date for selecting "final" configuration is April

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Symmetry-related issues need resolution

- **TF/port issues**
  - **A maximum of 2 diagnostic ports could wind up centered on symmetry planes**
  - **n=1 field errors from TF coils may be problematic -- *potential showstopper, early analysis required***
  - **maximum NBI tangency radius is only 1.3m with 20 coils --*increasing the tangency radius would require carving the TF coil outer leg conductor and case***
- **The 5 fold symmetry of the torque structure might affect the accessibility for large ancillary components**
- ***Need early allocation of ports and analysis of diagnostic sightlines and NBI beam envelopes***

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TF symmetry could be restored by using only 18 TF coils

- Larger horizontal ports could be provided
- NBI tangency radius could move out >1.3m
- Diagnostic access possible on all 6 symmetry planes (barring occlusion by saddle coils)
- But NOT without drawbacks
  - Feasibility not assured (would require shims in nose region, redesign of hydraulic clamps and interfaces with torque structure…)
  - TF ripple would go up
  - Maximum toroidal field and flattop would be reduced
  - Increased cost
  - Symmetry issues with torque structure would remain

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Space limitations in PBX might allow only a single coil layer

- Saddle coils need to be close to the plasma to minimize current requirements and coil complexity
- Current radial build allocations fix put the outer boundary of the HF coil assembly 23cm from the plasma
- The space available between the HF coil assembly and present VV is only 4.4cm
  - space is required for radial ribs and thermal insulation
  - inboard midplane location appears favorable for leads

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Analyses underway to assess adequacy of HF coil assembly

- Structural analysis of HF coil assembly for c10 plasma currently underway -- should determine space requirements for HF coil assembly structure
- EM analysis of reference design scenario will be reported by Art Brooks
  - first filter to see if single coil layer is acceptable
  - subsequent studies of islands and plasma properties (stability and confinement) required
- Subsequent studies will assess what could be gained by other coil topologies outside the saddle coil layer
  - a helical winding outside the saddle coils? a sawtooth winding? wavy PF coils? dipoles oriented normal to the saddle coil surface?

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Maintainability of cold mass is a serious concern

- PDX/PBX designed to be maintained from inside VV or outside TF -- only ex-vessel PF coils had difficult access because they were trapped in between
  - When OH solenoid developed a water leak, the corrective action was to air cool it and reduce the rep rate
- For the proposed configuration, the cold mass (HF coils, leads, instrumentation, and support structure) will be in a sealed enclosure that might not be accessible w/o dismantling the TF & PF coils and taking the cryostat lid off
- *A major effort is required just to find out what is wrong*
- LN2 cooling should preclude some coil failure modes (those associated with water leaks) but not all ...

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Reference design scenario has been proposed

- HF, TF, and PF coils energized prior to plasma initiation
  - Ramp times driven by power supply, coil voltage, and eddy current considerations
  - TF nominally constant throughout discharge
  - *Zero beta, zero current snapshot just prior to plasma initiation is first of 3 snapshots used to drive coil design*
- Plasma initiated with ECH
  - 0.1MW of ECH for 0.1s
  - ECH limits toroidal field levels for plasma initiation
  - LHD achieved equally good plasma initiation with NBI
    - NBI does not constrain toroidal field to narrow ranges
    - *Eliminate ECH from initial configuration? Save $?*

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Reference design scenario (2)

- **Plasma current ramped to full value**
  - **Poloidal flux from plasma current assumed necessary for confinement of beam ions**
  - **A ramp rate of 1MA/s would require 0.2s for a 200kA plasma**
  - ***Ramp rates should be on the fast side to drive coil voltages and power supply requirements -- is 1MA/s the right number?***
  - **Slower ramp rates can be accommodated at the expense of reduced time at high beta**
  - ***Zero beta, full current snapshot just prior to plasma heating is second of 3 snapshots used to drive coil design***

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Reference design scenario (3)

- **Plasma heated to full beta**
  - **Maximum auxiliary heating turned on with good energy confinement (consistent with achieving target beta values) to get maximum rate of stored energy increase**
  - ***0.1s duration?***
  - **May drive coil voltages and power supply requirements**
  - ***Full beta, full current snapshot is third of 3 snapshots used to drive coil design***
- **Maintain plasma at full current and full beta**
  - ***Goal: design the HF coils to be operated at the maximum field achievable with a plasma heating time of 0.3s***
  - **Shorter flattop times would underutilize the NBI system**
  - **Longer flattop times can be achieved at lower field**

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Reference design scenario (4)

- **Plasma beta and current ramped down to zero in controlled fashion**
  - ***0.2s?***
- **Ramp HF, TF and PF coils to zero current**
  - **Ramp times driven by power supply and coil voltage considerations**

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Stellarator Core Requirements

- **The HF coils are assumed to be a cryogenic temperatures for this class of plasma configurations because of the high current densities (>10kA/cm^2) at the desired field levels (>1T)**
- **The stellarator core consists of a *cryostat* surrounding a set of nested *saddle coils* mounted on a *shell structure* with radial ribs which surrounds the VV surrounding the plasma**
- **The stellarator core will be installed as a complete, pre-tested module**

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Cryostat Requirements

- The cryostat isolates the cryogenic coils from the room temperature environment of the test cell -- it also separates the water-cooled coils from LN2-cooled coils
- Insulation must be provided to keep the temperature on the exterior of the cryostat above the dew point temperature in the test cell -- heating elements may be required
- The vacuum vessel isolates the cryogenic coils from the ultra-high vacuum region of the plasma
- Insulation must be provided to shield the organically insulated coils during bakeout (350C) of the vacuum vessel
- The insulation also shields the vacuum vessel (at 293K) from the cryogenic coils (at 80K) during normal operation

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Support Arrangement

- **The HF shell structure is supported off the lower base structure on which the TF coils also rest**
  - **The HF shell structure must have low heat leakage and accommodate the thermal displacements associated with cooldown to cryogenic temperatures**
  - **Upon cooldown, the HF coil midplane should coincide with the TF and PF coil midplanes**
- ***The vacuum vessel is supported off the HF shell structure at discrete locations on the inboard and outboard midplane (?)***
  - **This arrangement provides optimal structural support for the VV, keeps the VV midplane coincident with the HF coil midplane during bakeout and operating conditions, and simplifies the interface where the VV horizontal ports penetrate the cryostat**
- ***The cryostat is also supported off the HF shell structure (?)***

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HF Coil Cooling

- **HF coils are maintained in a cold, gaseous nitrogen environment at a pressure slightly above 1 atmosphere, vented to outside**
- **The coils are cooled with liquid nitrogen with a nominal temperature of 80K**
- **Liquid nitrogen is brought on site via trucks -- no on-site refrigeration is required**
- **Warmup and cooldown times from 293K to 80K shall be less than 1 week**
- **Special provisions might be required to avoid compromising the integrity of the high temperature insulation surrounding the vacuum vessel by wetting with liquid nitrogen**
- ***Trade studies should be conducted to identified the best means of cooling the HF coils -- in closed conduits? by spraying through nozzles? other?***

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HF Coil Performance Requirements

- **HF coils are required to carry the currents attendant with the reference design scenario**
  - **The prescribed currents must provide the desired plasma shape and not significantly compromise plasma stability and confinement properties**
  - **Islands can compromise plasma confinement -- *the total area of islands in the plasma cross-section due to the HF coils must be less than 10% of the plasma cross-sectional area (?)***
- ***The capability to independently power the HF coils (with mirrored and rotated coils always in the same circuit) w/o disassembling the TF coils shall be provided***

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HF Coil Performance Requirements (2)

- **The minimum number of independent circuits for initial operation will be discussed by Brooks today**
- ***HF coils will be feedback controlled -- the control algorithm should monitor the harmonic content of the error fields (?)***
- ***HF coils shall provide the capability to correct low order field errors not attributable to the HF coils in their nominal position (?)***
  - **Other sources of field error include:**
    - **HF, TF, and PF coil placement, feeds, and transitions**
    - **magnetic material**
    - **eddy currents**
  - **Required harmonics and magnitudes of field errors are TBD**
  - **Assess field errors in PBX prior to disassembly (?)**

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Accurate conductor placement is essential

- ***The centroid of the conductor must be within 1.5mm of its nominal position***
  - **Historical value is ~ 0.1% of major radius**
    - **R=1.5m (NCSX) -> 1.5mm**
    - **R=3.96m (LHD) -> 4.0mm, they used 2mm**
  - ***How are we going to measure this during assembly and installation?***
- **Accurate placement is achieved through precision slots machined in rigid, stable shell**

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Field errors from coil transitions and leads must be low

- Each coil will be wound with 2 spiral pancakes (avoiding sharp jogs between layers)
- Spiral pancakes will be joined in root of deep slot by a short jog
- Adjacent coils will have oppositely directed jogs
- Coil currents will be kept low (10kA max, 5kA goal)
- Coaxial or twisted pair current feeds will be used inside the cryostat
- Lead geometries will be designed to minimize field errors -- using tight radius bends, for instance
- Stellarator symmetry will be preserved

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Field errors due to magnetic materials must also be low

- The permeability of stainless steel can be dramatically changed during welding and forming
- The use of stainless steel (or other magnetic materials) in structures required welding and forming is discouraged
  - The closer the structure is to the plasma (e.g. the vacuum vessel), the more important is this consideration
- In cases where magnetic materials cannot be avoided, it must be demonstrated that the resulting field errors will not have an unacceptable effect on the plasma

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Time constant of shell

- **Current guidance has been to keep the eddy current time constants low (order 10ms) to avoid stabilizing kink modes on the time scale of a discharge**
- **This drives us to conducting shells with many insulating breaks or a non-conducting shell**
- **Fiber-reinforced plastic shells tend to have low strength, a CTE that is twice that of copper, and poor machinability**
- **Bronze shells have good strength, are easy to cast, easy to machine, have CTEs that match well with copper, and fairly high electrical resistivity (10x copper)**
- ***Propose relaxing requirement to order 200ms with***
  - ***a shape that approximates the local flux surface and***
  - ***instrumentation to monitor eddy currents excited by kink modes***

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PF coils

- New PF coils will be required to augment outboard PF coils
  - Replace some of the in-vessel PF coils which will be removed
  - Supported by Brooks' study
- New OH solenoid appears in order
  - Exisiting OH solenoid is unnecessarily complex
  - More importantly, it leaks
  - Other OH coils can be retained
- OH requirement for PBX was 3 V-s
  - Should be adequate for lower current NCSX

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Vacuum vessel and PFCs

- A close fitting (outside a ~2cm SOL), vacuum tight liner shall be provided
- The vacuum vessel shall be capable of being completely armored with carbon tiles
- The vacuum vessel shall be initially armored with carbon tiles as required to support Phase I experimental objectives
- One poloidal limiter per period shall be provided
- The vacuum vessel and all in-vessel components shall be bakeable to 350C
- Components near port attachments shall be bakeable to 150C
- Local armor may be required for NB shinethrough and ripple losses
- Provisions for GDC, boronization, and lithium coating shall be made
- The decay time constant for eddy currents in the vacuum vessel shall not exceed timescales over which changes in I_p are effected
  - *100ms (?)*
  - The vacuum vessel shall be instrumented to detect eddy currents acting to stabilize kink modes

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Auxiliary heating

NBI			
Beamlines	4		Co-tangential PBX beamlines (due to insufficient poloidal flux for counter-tangential beams at low field) Provisions for one counter-tangential beamline shall be made
Power	6	MW	Power to plasma
Tangency radius	1.3	m	Maximum tangency radius on PBX
Pulse length	0.3	s	Initial configuration
	3	s	Upgrade configuration
ICH			
Power	6	MW	Upgrade configuration; no ICH in TPC
Pulse length	3	s	Upgrade configuration
Frequency range	?	MHz	
Antenna configuration	?		
ECH			
Power	0.1	MW	Initial configuration
	2	MW	Upgrade configuration
Pulse length	0.1	s	Initial configuration
	3	s	Upgrade configuration
Frequency	?	GHz	
Launcher location	?		

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Cost & schedule

- First plasma targeted for September, 2003
  - Consistent with FWP guidelines
- Preliminary cost objectives shall be derived from December, 1998 cost study
  - Option 2c cost to be built up from estimates of other options
  - Cost objectives will be allocated to 2-digit WBS level

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Summary

- A set of working requirements is in place
  - Based on Option 2c -- providing a modular stellarator core with a solid VV that is dropped into PBX
- Design impacts of this choice have been identified
- Key issues flagged, project guidance sought
  - Reference design scenario OK as is?
  - FEC requirements for HF coils?
  - Time constant requirements of VV? Shell?
  - NB tangency radius of 1.3m OK?
  - Field error criterion of <10% of toroidal flux?