NCSX
Experiment Goals & Requirements

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NCSX PAC Meeting
2 November 1998

Outline

- Goals → Plans → Requirements
- Physics Requirements Document (PRD)
- Analysis and Optimization of Requirements
- Next step studies → PVR

Experiment Goals

Develop, demonstrate, test understanding of attractive compact stellarator configurations

– establish basis for whether they can be an attractive fusion reactor (~ Aries-RS)

– with bootstrap consistent equilibria

- Ability to operate at $<\beta>$ ~ 4 - 5% without disruptions
  what ι_{ext} is required to avoid disruptions at high β ?

- Determine β-limit, limiting mechanisms, and scaling

- Test adequacy of neoclassical transport optimization
  and projection to reactor-scale

- Test ability to control transport; obtain enhanced confinement; measure confinement scaling.

- Test bootstrap current stabilization of equilib. islands & neoclassical tearing

- Start exploration of edge designs for power and particle exhaust control in compact stellarators

Establish basis for decisions on next scale experiments

Proof-of-Performance

Physics Requirements Document

- Document the requirements for design and engineering

- Communicate within the group

⇒ Working document
  – state of our knowledge and *lack*
  – goals

⇒ facilitate search for optimum value for cost

- Requirements need to be justified and substantiated
  - series of memos documenting analysis and choices
  - group meeting talks, slides on web

- Initial draft undergoing comment within group
  Available on web via: http://fileroom.pppl.gov/ncsx/

- Issue formally at PVR

Goal: maximize physics and minimize costs

Expected Research Campaigns

1	~ 2 m	Initial plasma operation and shakedown
2	~ 4 m	Field-line mapping
3	~ 1 y	Plasma Heating(NBI, short pulse) & Diag. Commissioning • Study density limits & disruptions, neocl. optimization, velocity damping, • initial boundary control, initial RF coupling studies • at end: beta push, can we challenge beta limit with initial power?
		Add diagnostics, *possible plasma edge design modification*
4	~ 6 m	Confinement optimization • explore methods for enhancing confinement: sheared v_φ, edge conditioning and coatings, pellet injection
		Add diagnostics, *possible heating power upgrade*
5	~ 1 y	High beta studies (short pulse) • can we get to beta-limit? Study limiting mechanisms • disruption boundaries • continue confinement improvement studies (current profile equilibration via evolution control)
		Extend heating pulse length, plasma edge design upgrade, *possible heating power upgrade*
6	~ 1 y	Long pulse operation at high-beta • heating system and edge recommisioning • test j(r) equilibration • disruption boundaries in long pulse • transport stationarity

Save construction costs by phasing capabilities to match research progression

- heating systems, diagnostics, edge power handling

Plasma Requirements

Goals should be studied in a compact stellarator in a plasma regime relevant to future power plants

- collisionless plasmas, high temperatures and densities
- lower aspect ratio than previously obtained: $\langle A \rangle < 4$
- (ultimately) fully relaxed, non-inductively sustained current profiles

Reference design plasmas should be stable

- ballooning and kink \
- vertical; n = 0 / Disruption stability
- neoclassical tearing

Experiment should demonstrate stability with bootstrap consistent profiles, at a level not otherwise obtainable (without conducting walls)

- choose goal of $\beta \sim 4\%$
- allow modest near-axis seed-current (<5% of edge iota), to give control of core-shear

Plasma Requirements, cont'd

Need substantial iota from coils (not from plasma currents)

- to reduce non-linear sensitivity of equilibrium to bootstrap current at high-β
- target: $\geq$ 40% of iota from coils

Need adequate confinement to access $\beta \sim 4\%$ with available power (NB ~ 6MW to start)

- Neutral-Beam ion confinement
- Neutral-Beam CX losses
- thermal confinement

Requirement Analysis

Use axisymmetric expressions and codes to set minimum requirements and general characteristics. Evaluate candidate configurations with full 3D codes.

Neutral-Beam ion confinement

- want < 20% fast ion loss to ensure adequacy of heating power, reduce uncertainty of analysis

Neutral-Beam CX losses

- want < 20% CX loss of NB power
- based on Transp study (1D neutrals),
  need $n_e \langle a \rangle > 2.e19\ m^{-2}$

Thermal confinement

- $\tau_E = 2.3\ \tau_E^{ISS95}$
  - roughly as obtained on W7-AS
  - for PBX-M size and elongation, corresponds to $\tau_E^{ITER\text{-}89P}$ (due to different A and κ scalings)

- $\tau_E^{neo} \geq 2\ \tau_E$

- Want any equilibrium islands to be less than 10% of flux (aggregate).

Spreadsheet model for sizing

Determine (roughly) machine parameters to aim at which satisfy constraints

Vary (R, a, B, n) to achieve:

$\beta \geq 4\%$ with $P_{heat} = 6MW$
$\tau_E = 2.3\ \tau_E^{ISS95}$
Reactor-like collisionality: $nR/T^2 \leq 2$

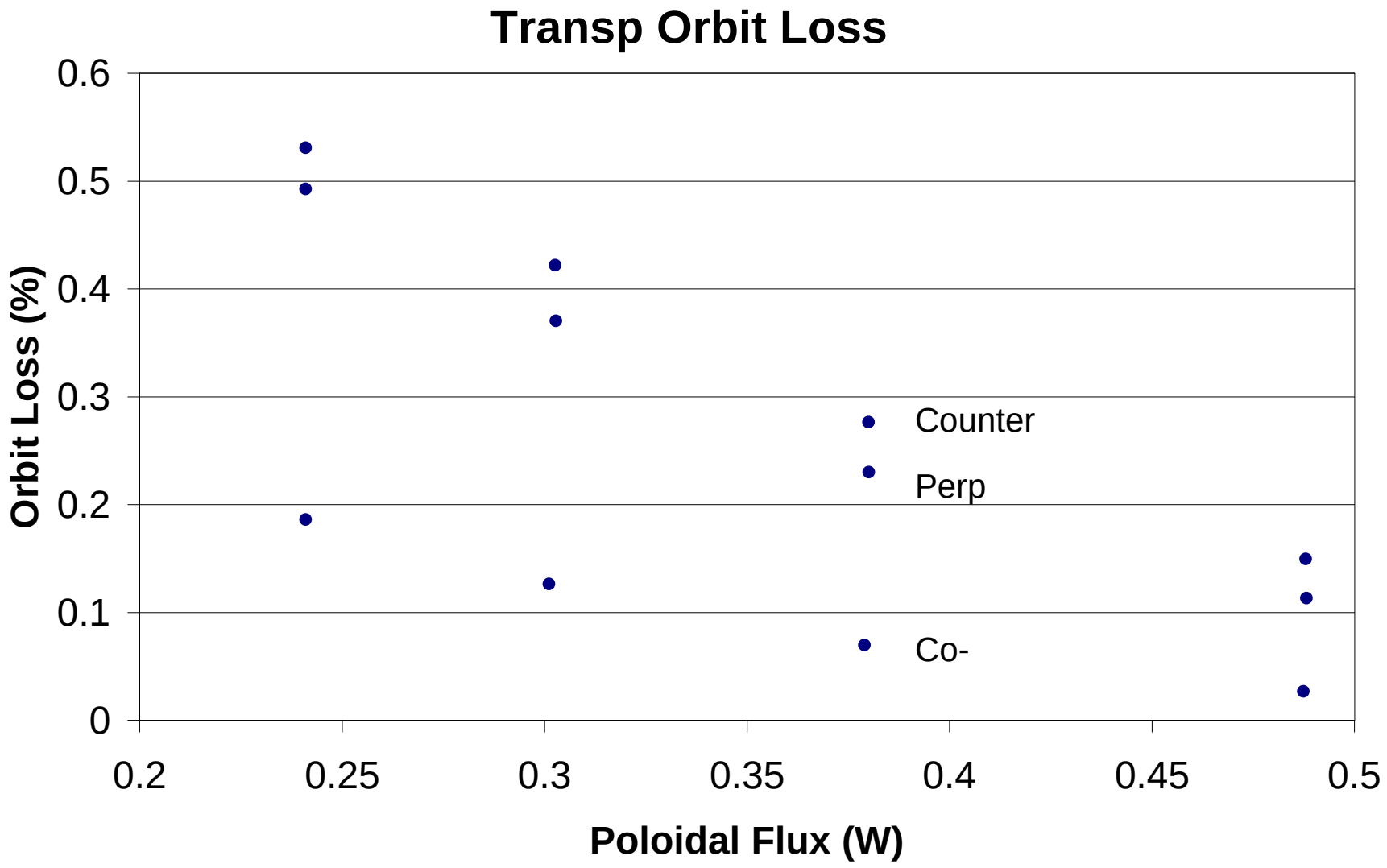
$n_e \leq$ Sudo-density limit
$n_e \langle a \rangle \geq$ 1.98e19 m-2 $\Rightarrow$20% CX NB loss (Transp)

ψ_P sufficient for ≤20% orbit loss (axisymmetric)
for 40keV D tangential NBI (calib to Transp).
- for inside-PBX sized experiment (R=1.42m, <a>=0.42):
  need ~0.24 W for co-injection
  need ~0.43 W for counter-injection

$\tau_E^{neo} \geq 2\ \tau_E$ (axisymmetric)

$\tau_{pulse} \equiv 3\ \tau_{L/R} < 4$ sec

Also calculates current in a modular-coil set and approximate (normalized) coil size, to give a glimpse into the engineering tradeoffs.


Transp Orbit Loss
Orbit Loss (%)
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Poloidal Flux (W)
Counter
Perp
Co-

Spread Sheet Optimizaions

Configuration	QAS3-c10 inside PBX-M		QAS3-i55 new VV	
		min P for 4%	min coil A-m for 4%	optimize A min P for 4%
<iota>	0.35	0.35	0.34	0.34
iota(a)	0.47	0.47	0.47	0.47
R/a	3.43	3.43	2.76	1.28
R (m)	1.45	1.45	1.19	0.76
<a> (m)	0.42	0.42	0.43	0.60
B(T) edge	1.23	1.27	1.26	0.91
P(MW)	6.00	7.91	6.00	1.95
n (10^19/m^3)	5.51	7.10	7.47	5.60
tauE = 2.3*ISS95 (s)	0.025	0.025	0.027	0.054
beta	0.033	0.040	0.040	0.040
To (2<T>) (keV)	2.22	2.27	2.11	1.46
tau_pulse = 3*L/R	3.78	3.89	3.60	4.00
poloidal flux (W)	0.23	0.24	0.24	0.34
ctr-inj. Flux req. (W)	0.62	0.62	0.57	0.57
chi-neo (m^2/s)	1.01	1.14	1.03	0.76
tau-E-neo (s) (axisym	0.097	0.086	0.099	0.258

Zeff=2 assumed

Wall and Vessel Requirements

- Expect to use carbon limiters to handle initial short-pulse power exhaust
  - Edge iota not fixed, cannot design island divertors in beginning

- Limit initial wall carbon armor to handling beam shine-through and possible high flux ripple loss-regions
  - Upgrade as add power and pulse-length

- For inside-PBX option, requiring a liner to limit conductance between internal hardware and plasma

- Based on tokamak experience, require that carbon PFC's must be baked to 350 °C. All other internal hardware to 150 °C.

- Require conducting structures on low-field side of plasma be set back to > 1.3a, to prevent conducting wall stabilization of external-kinks.

  Need $\gamma_{ideal}\ \tau_{res} < 1$ inside 1.3a

Plasma Requirements

Next Steps

- Flexibility required by Physics Goals
  - range of n_e, $\langle\iota\rangle$, I_P ?
  - range of $\langle\kappa\rangle$, $\langle\delta\rangle$, 3D shaping?
  - expected range of pressure and current profile shapes 'robustness studies'
  - what are required heating characteristics? (e.g. NB aiming)

some aspects are clear:

- need ability to make kink stable & unstable
- need factor of ~2 range in B for transport scaling studies. Would provide flux for counter-NBI $\Rightarrow$ need to be able to re-orient beams.
- want ability to control/compensate resonant field perturbations

- Diagnostics requirements at each phase

Plasma Evolution Studies

Evaluating candidate coil configurations

- OH-CD target plasma scenario
  - use OH current to achieve needed $\langle \iota \rangle$ and n_e to start NBI
  - evaluate V-s consumption and requirements

  Likely plan: modify 3D-Whist for current evolution

- Non-CD target plasma scenario
  - Can shape evolution be used to achieve needed $\langle \iota \rangle$ to start NBI ?
  - heating and densification requirements
    e.g. ECH/ICRF scenario like CHS

- Evolution during heating
  - evolution of $\iota(s)$, equilibrium
  - low and high-β
  - short and long pulse

<u>In all three cases</u>:

- develop control and coil flexibility requirements
- evaluate candidate coils' ability to meet requirements

Plasma/Wall Studies

Next Steps

- Wall coating requirements & strategies
  - for vacuum cleanliness
  - for improved confinement & recycling control
- Limiter requirements and characteristics
  - number, size, likely locations
  - space envelope for later phases
- Localized power handling
  - field line tracing for localized particle loss
  - NB protective plates
- Foreseeable divertor requirements
  - likely locations
  - space envelope required

Summary

- Experiment goals are being mapped to Physics Requirements

- Draft PRD is being used to negotiate requirements with engineering design

  - goal is cost-effective experiment

- Spreadsheet-based 0-D model has focused configuration designs

- Next major efforts, as candidate configurations and coils mature:

  - flexibility and robustness studies → requirements
  - power handling requirements