Fusion Nuclear Science Facility (FNSF) Divertor Plans and Research Options

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FNSF Divertor Requirements

- **Heat flux**
  - Dissipation of <10 MW/m² in steady-state (similar to ITER)
  - At lower A, heat fluxes tend to be higher for geometric reasons
    - Power is compressed into small divertor area (low R)
    - Connection lengths are short

- **Fuel and Helium Exhaust**
  - Adequate fuel exhaust for density control
  - Adequate helium exhaust to maintain $f_{He} < 10\%$

- **Core performance**
  - Compatibility with good core confinement and stability
  - Compatibility with current drive (more stringent at lower A)

- **Geometry**
  - Compact design for contained machine cost

- **Plasma material interface**
  - Compatibility with high neutron flux
Baseline Approach for FDF (FNSF-AT) Is a Balanced Double-null Divertor Configuration

- Higher triangularity easier in balanced double-null (DN) configuration
  - Stability and confinement improve with increasing triangularity
- Particle and heat flux in DN is mostly to the outboard divertor (~80%)
- DN configuration and tilted divertor plates reduce peak heat flux by increasing total wetted area of divertor surfaces
  - Angle between magnetic field line and divertor tile surface ~1°
- Closure to impede mobility of neutrals away from divertor and facilitate pumping
- Optimal design may not be exactly up/down symmetric because of effect of ExB drifts

![Diagram showing FDF equilibrium and divertor target plate with flow to pump]
Precise Alignment of Divertor Plates and High Core Radiation Are Key to Manageable Heat-loading in FNSF-AT

- Well aligned tiles -> B-target angle ~1° (FDF) vs. ~2.5° (ITER)
- ~50% core radiation fraction -> Psol/Rdiv ~21.7 (FDF) vs. ~18 (ITER)
- Results from both simple and 2-D plasma modeling analysis predict peak heat flux < 10 MW/m² at outer divertor targets
  - Multi-machine, multi-parameter scaling from Loarte 1999
  - SOLPS (Scrape Off Layer Plasma Simulation): 2D plasma fluid code (B2.5), Monte Carlo neutrals code (Eirene)
- Several approaches can be used in parallel to further reduce peak heat flux
  - Flux expansion (X divertor, SX divertor, Snowflake divertor)
  - SOL and divertor radiative dissipation
  - Rotating RMP (3D edge)
SOLPS Modeling Shows Strong Reduction of Peak Heat Flux with Increasing Gas Puff

- ITER heat and particle diffusion coefficients in the SOL, lower in the pedestal
- Core boundary conditions from Chan, FS&T 2010
- Low gas-puff case (conduction-limited case to compare heat flux width to empirical scalings)
  - $T_{e,OSP} \sim 150$ eV,
- Medium gas puff case
  - $T_{e,OSP} \sim 12$ eV,
- High gas puff case (nearly detached)
  - $T_{e,OSP} \sim 2$ eV,
DIII-D Shows Radiative Dissipation and Stochastic Edge Viable Approaches to Reducing Peak Heat Flux

- Divertor radiation preferentially enhanced using puff and pump technique

- $P_{\text{rad}}/P_{\text{NBI}} \sim 60\%$ with $Z_{\text{eff}} \sim 2.0$
  - Argon and D2 injection

- $\beta_n=2.6$, $H_{89}=2.0$, $G=0.4$ maintained
  - Experiments thus far focused on puff and pump studies, not fusion performance

- Resonant Magnetic Perturbation splits strike points

- Angular rotation of the RMP will result in a time averaged broadening of the OSP footprint
Novel Solutions May Be Required to for Successful Power Handling

- Several options are available
  - Novel geometries, e.g. Snowflake, SuperX
  - New materials, liquid walls

- The SuperX Divertor (SXD) directly addresses the ST geometric disadvantages
  - Increased $R_{\text{div}}$ -> more wetted area
  - Longer connection lengths

*D. Ryutov, PoP 15 (2008) 092501

*P. Valanju, APS08
Unmitigated Heat Flux in a Low-A FNSF May Be Unacceptably High

- Geometry from Peng, PPCF 2005
- Core density, power from Peng IAEA FEC2008
- Target loads calculated with SOLPS
  - ITER radial transport

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The Super-X Divertor Has the Potential to Resolve the Heat Flux Problem for FNSF

- Calculated peak heat flux is reduced to ~7 MW/m² with SXD
  - Could be further reduced with impurity seeding

- Heat flux reduction is promising, but full PMI needs to be considered in simulations
  - Helium pumping
  - Erosion, material migration
  - Impact off-normal events
FNSF Engineering Constraints on the SXD Need to Be Considered

- Some questions to consider
  - How many PF coils are required?
  - Can they be located to avoid interference with other internal components?
  - Will they require additional shielding?
  - How far can the divertor be extended consistent with vertical drop remote handling?
  - Will SXD allow neutron shielding of the divertor?
  - Can heat flux be low enough to relax divertor design?

- Costs and benefits need to be addressed
Partial Detachment with Significant Reduction of Heat Flux Observed in “Snowflake” Divertor on NSTX

- Reduction observed in 2-3 mm region (mapped to midplane) adjacent to separatrix
- Shown heat fluxes are in uncalibrated relative units (IR camera data not calibrated due to lithium coatings)

FNSF Is Well Positioned to Address DEMO Divertor Design Issues

Expected progress:

- Refinements to methodologies, including addition of particle drifts to SOLPS analyses
- New, more reliable empirical scalings likely to result from Joint (C-Mod, NSTX, DIII-D) Joule Milestone for 2010 on SOL thermal transport physics
- Experimental tests of Snowflake and SXD concepts
- Experimental validation of integrated performance
- Refinements to divertor design, e.g. up/down asymmetry to account for effect of ExB drifts
- Engineering analysis to study FNSF implementation
  - Design must be made consistent with facility goals