Progress in Aries AT Physics Modeling

- Aries AT : non inductive,steady state,self consistent transport,mhd,current drive and stability is sought.
- Density scans parameterized by the value of β_n pedestal presented.
- Pedestal stability was investigated using Eped type stability analysis.
- Approach requires tedious manual iteration and data manipulation between transport, equilibrium and stability codes using EFIT,ONETWO,GCNMP and ELITE.
- We are developing an integrated modeling and fitting framework to cope with these issues.
- Methods and results achieved using glf will be extended to use the much more computationally expensive tglf model in the future.

IMFIT EPED Module

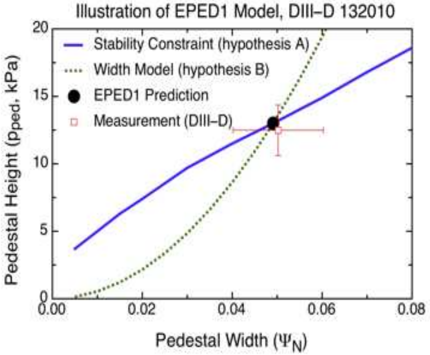
- Pedestal height/width modeling using the EPED1 prescription requires
  - Peeling-ballooning stability boundary prediction. Obtained by generating parametrically scanned equilibria involving 8 parameters: $B_T, I_p, R, a, \kappa, \delta, \beta, n_{e,p}$ Equilibria are used in Elite to obtain stability boundary.
  - Kinetic ballooning mode turbulence constraint which is fixed and known ($\Delta = 0.076\sqrt{\beta_{p,ped}}$) for Eped1.
- In results shown below we used $B_T = 5.4, I_p = 10.6, R = 5.5, a = 1.4, k = 2.2, \delta = .78, 1.6 < \beta < 5.6, ne_{ped} = 1.1e19, press_{ped} = 1.6KPa, \beta_{nped} = 1.0, \rho_{ped} = 0.92$
- Eped model with $\beta_n = 5.7$ indicates that pedestal pressure can be raised to at least 1.8 KPA with $\rho_{ped} = 0.90$

Mechanics of the EPED1 Predictive Model

- **Input: B_t, I_p, R, a, κ, δ, n_{ped}, β_{global}**
- **Output: Pedestal height and width**

*P.B. Snyder et al PoP **16** 056118 (2009)*

- **Stability calculated via a series of model equilibria with increasing pedestal height**
  - ELITE, n=5-30, $\gamma > \omega_{*pi}/2$
- **Width (KBM):** $\Delta_{\psi_N} = 0.076\beta_{p,ped}^{1/2}$



- **Different width dependence of stability (roughly $p_{ped} \sim \Delta_\psi^{3/4}$) and width model ($p_{ped} \sim \Delta_\psi^2$) ensure unique nontrivial solution, which is the EPED1 prediction (black circle)** ***[both constraints needed to get height or width]***
  - Can be systematically compared to existing data or future experiments

Stability and width physics are tightly coupled: If either stability or width physics model is incorrect, predictions for both height and width will be systematically incorrect

Pedestal Transport grid requirements

- Expensive flux evaluation $==>$ want coarse grid
- Sensitivity to gradients $==>$ want fine grid
- Turbulent transport theories average over ion gyro radii, $\Delta\rho => 0$ not physical
- Variable pedestal location $==>$ want non uniform grid
- Three fixed points on transport grid:

  bc 1 at $\rho = 0$
  bc 2 at $\rho = \rho_p$ (ρ_p varies with mhd)
  bc 3 at $\rho = \rho_a(separatrix)$ (total current bc)
- Satisfy all requirements by using higher order derivatives ("compact schemes"), non uniform,adaptive grids

Non uniform compact scheme meets requirements

- Turbulent transport is sensitive to order of interpolation schemes.
- Compact schemes yield higher order methods that require the solution of tridiagonal or pentadiagonal systems of equations to obtain the interpolant or derivatives across the grid at all points simultaneously.
- High order approximation to derivatives on non uniform grid are based on expansion in powers of $h_i = \rho_i - \rho_{i-1}$. Compare derivatives of like order to get equations for coefficients $(\alpha, \beta, A_i, B_i, C_i, Di, F_i)$

$$\alpha f^{'}_{i-1} + f^{'}_{i} + \beta f^{'}_{i+1} = \qquad (1)$$

$$D_i f_{i-2} + C_i f_{i+2} + B_i f_{i-1} + A_i f_{i+1} + F_i f_i$$

Glf/Tglf Flux solver

- Use Jacobian free methods due to computational expense.
- Only fluxes are determined: Solve transport equations with fluxes directly:

$$\underline{\underline{M}}\frac{\partial}{\partial t}\bigg|_{\zeta}\underline{u} - \frac{1}{H\rho}\frac{\partial}{\partial \rho}\left(H\rho\underline{\Gamma}\right) + \underline{\underline{W}}\,\underline{u} = \underline{S} \tag{2}$$

- Typically boundary conditions applied at $\rho = 0$ and $\rho = \rho_b$ with $0 < \rho_b <= 1.0$:

$$\lim_{\rho\to 0}\left(H\rho\Gamma(\rho)\right) = 0 \tag{3}$$

$$\alpha n_i(\rho_b) + \beta\Gamma(\rho_b) = S_b(t) \tag{4}$$

- The flux vector $\underline{\Gamma}$ represents the flow of electrons,ions, energy and momentum and poloidal magnetic flux and is obtained from the confinement models directly.

Steady state current drive

- Developed solution method to solve flux surface averaged Faraday's law in steady state directly:

$$\frac{1}{FG(H\rho)^2}\frac{\partial(FGH\rho B_{p0})}{\partial t} = \frac{1}{H\rho}\frac{\partial E_0}{\partial \rho} \qquad (5)$$

  needed because current relaxation $>$ 100 sec in fusion type devices. Standard relaxation to steady state not feasible with turbulent transport models.

- Inductive current is proportional to inverse of resistivity:

$$E_0 \equiv H\left\langle \frac{\vec{E}\cdot\vec{B}}{B_{T_0}} \right\rangle = \eta_{\parallel} H \left\langle \frac{\vec{J_{ohm}}\cdot\vec{B}}{B_{T_0}} \right\rangle . \qquad (6)$$

Density scaling

- Density profile shape is crucial in obtaining reasonable performance parameters using only fusion heating.
- Developed method that allows a prescribed normalized beta value to be specified at a suitable pedestal location.
- The density profile inside the pedestal region is parametrized using a cubic spline approach.
- Primary ion density at ρ_{ped} is determined by given value of β_{nped}
- Density at magnetic axis is fixed by zero gradient condition.
- Shape of density is controlled by number of knot points.
- Secondary ions and electrons are scaled to be consistent with the primary ion density and zeff.

Aries base case

Efit generation of $\beta_n = 4.8$ Aries equilibrium:

Minor radius a (cm): 139.9	b/a: 2.29
R at mag. axis (cm): 580.1	Z at mag. axis (cm): 0.0
Volume (cm**3): 4.22E+08	Pol. circum. (cm): 1519.1
Bt (G): 5.54E+04	Ip (A): 1.06E+07
L-avg den (1/cm**3): 1.61E+14	Tau-particle-dt (s): 2.000
profiles ucenter	uedge
elec. den. (1/cm**3): 1.95E+14	7.95E+13
elec. temp. (keV): 26.46	0.02
ion temp. (keV): 26.46	0.02
current (A/cm**2): 52.79	1.73
Zeff: 1.27	1.44
q: 3.16	17.50
Brems prim ions (W): 2.21E+07	imp ions : 4.36E+07
beta 6.7	Beta-p: 2.62 beta-n 4.8

Aries base case,profiles

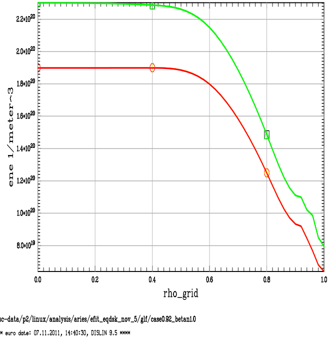


Figure: Initial density $\beta_{nped} = 1.0$

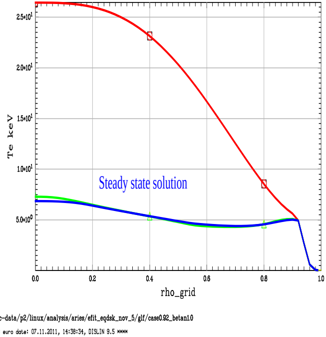


Figure: Base case and simulated Te,Ti

GIf Sensitivity to boundary location

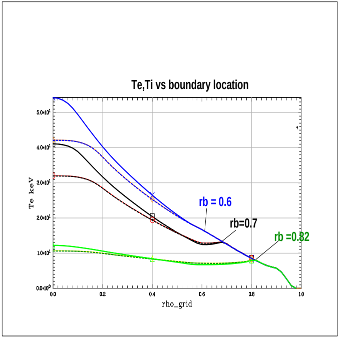


Figure: Temperatures fixed beyond rb value

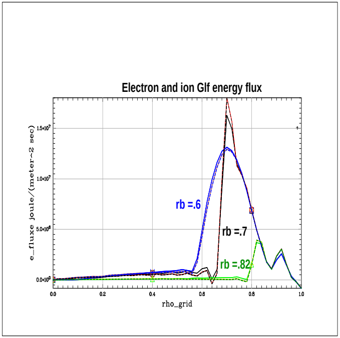


Figure: GIf active outside rb value

GENERAL ATOMICS

Aries Density scan I , Electrons at $\beta_{n-ped} = 1$

$\beta_n = 1.6, 3.8, 5.6$ (low to high density)

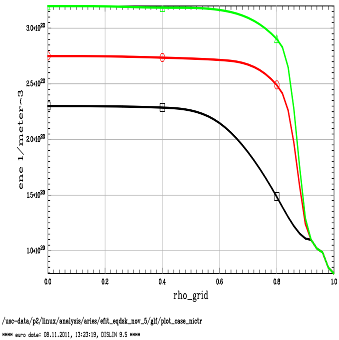


Figure: Electron density

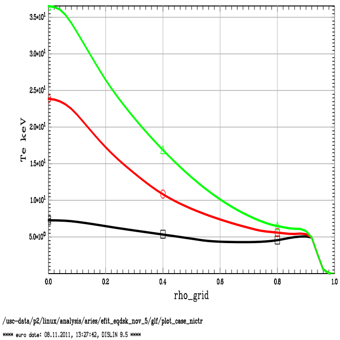


Figure: Glf simulated Te

GENERAL ATOMICS

Aries Density scan I , Ions at $\beta_{n-ped} = 1$

$\overline{n_e} = 2.9x10^{20}, P_{DT} = 2900Mw$

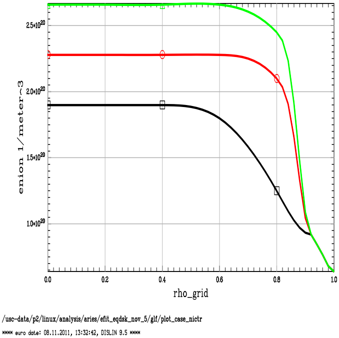


Figure: Ion density

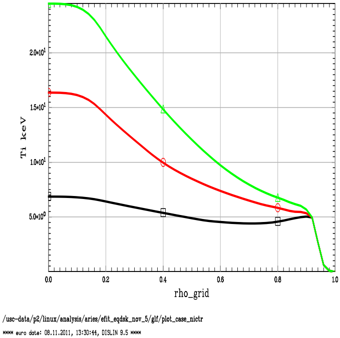


Figure: Glf simulated Ti

GENERAL ATOMICS

Time evolution I,electrons,ions $\beta_{n-ped} = 1$

GIf electron and ion dynamics lead to different $Te(0)$, $Ti(0)$ Initial rise in Te(0),Ti(0) then decays on time scale of 300 msec. $\beta_n = 5.6 ==>$ green curve, steady state

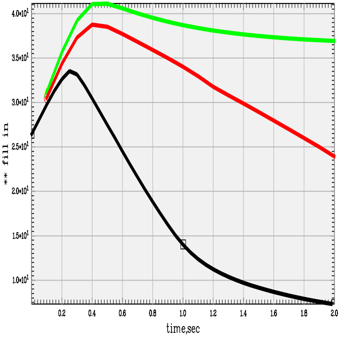


Figure: $Te(0)$

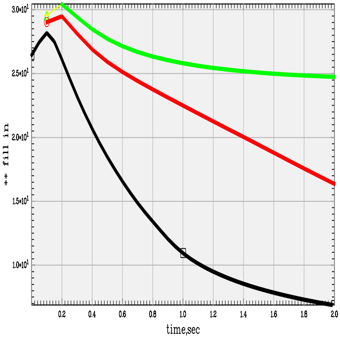
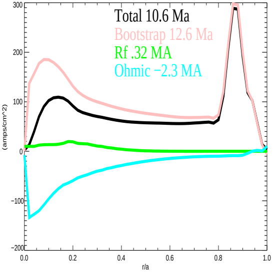
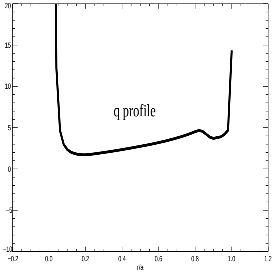


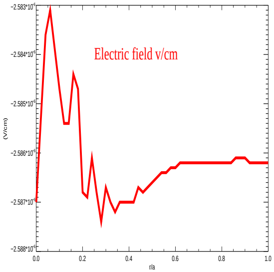
Figure: $Ti(0)$

Current drive I

- Large bootstrap near pedestal overdrives plasma. Fw near axis not feasible. Residual ohmic is large and negative ==> density shapeing near edge required.







Aries Density scan II, Electrons at $\beta_{n-ped} = 1$

$\beta_n = 1.6, 3.3, 4.9, 5.1$ (low to high density)

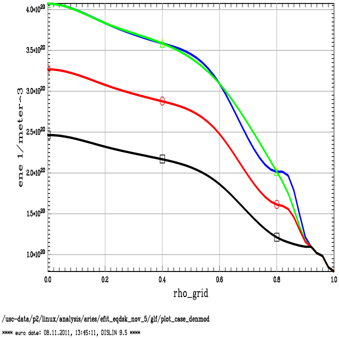


Figure: Density profiles used

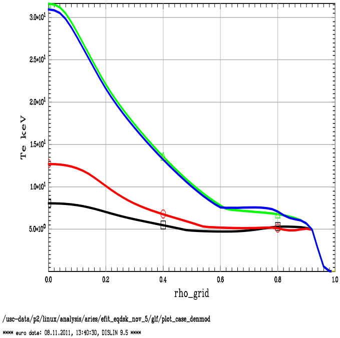


Figure: Glf simulated Te

GENERAL ATOMICS

Aries Density scan II, Ions at $\beta_{n-ped} = 1$

$\overline{n_e} = 3.5x10^{20}, P_{DT} = 2740Mw$

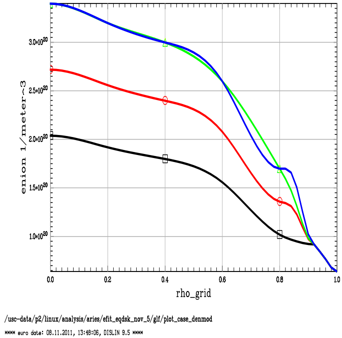


Figure: Density profiles used

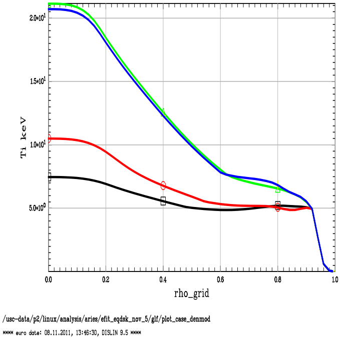


Figure: Glf simulated Ti

GENERAL ATOMICS

Time evolution II,electrons,ions $\beta_{n-ped} = 1$

Density profile fixed in all cases means that dynamics due to density gradients is invariant.

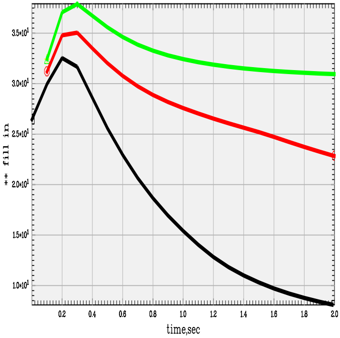


Figure: $Te(0)$

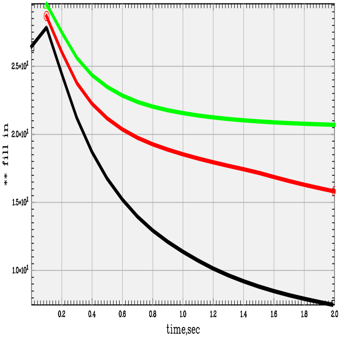


Figure: $Ti(0)$

GENERAL ATOMICS

Significant density peaking is not beneficial

Peaking causes energy flow $.2 < \rho < .4, \beta_n = 3.8$
No peaking has large energy flow further out $.5 < \rho < .9, \beta_n = 5.0$

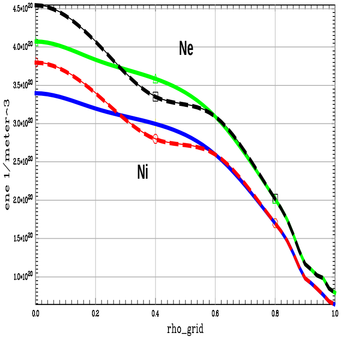


Figure: Elct,ion Densities

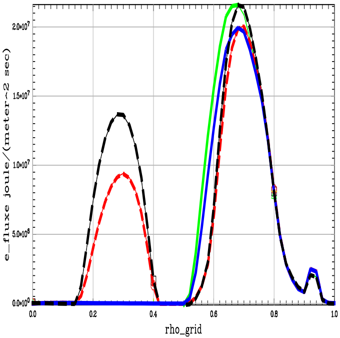


Figure: Electron and ion energy flux

Density peaking is not beneficial...

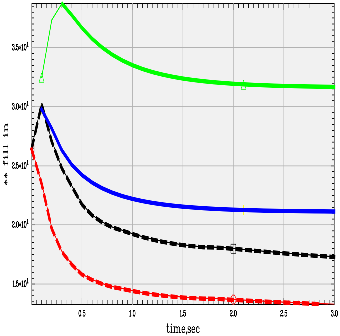


Figure: $Te(0)$, $Ti(0)$

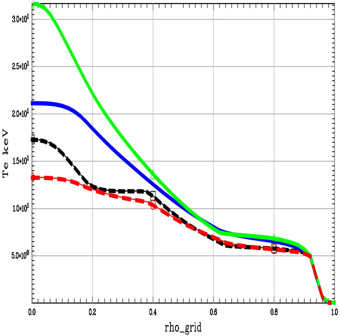
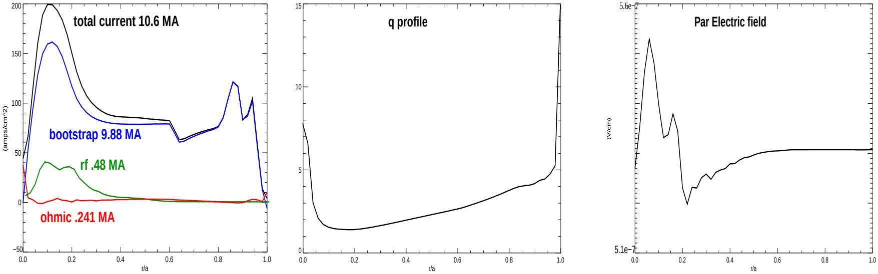


Figure: Steady state $Te(\rho)$, $Ti(\rho)$

GENERAL ATOMICS

Current drive II

- Need $\frac{50amps}{cm^2}$ on axis current drive required to drive inductive current close to zero ==> 40 MW of fast wave
- Ohmic current in steady state is 240 KA with .48 MA of rf



GENERAL ATOMICS

First results with tglf transport

$$\overline{n_e} = 1.7x10^{20}, P_{DT} = 740MW$$

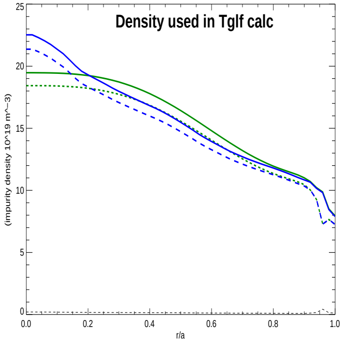


Figure: Elect,ion densities

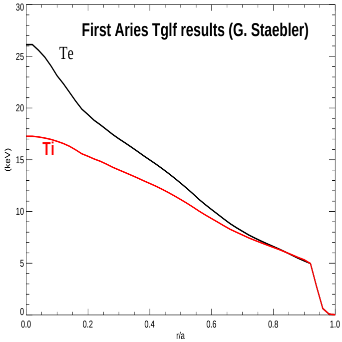


Figure: Electron and ion tglf temperatures(rb =0.8)

Summary

- With Glf confinement,on axis current drive,shaped ion density and impurity control and appropriate fuelling our analysis so far indicates that a β_n 5 AT ARIES scheme is workable from a physics perspective.
- Aries AT with $\beta_{n-ped} = 1$ will require higher density than currently proposed and/or auxiliary heating.
- Initial pedestal stability results indicate that $1. < \beta_{n-ped} < 1.1$, at ρ 0.9 is satisfactory.
- Good alignment of total current with bootstrap seems possible. But On axis current drive is needed to reduce the inductive (ohmic) current to an acceptable level.

Summary...

- Because densities were not evolved in this study, the glf electron ion dynamics due to density gradients is an invariant of the simulations.
- We are developing a framework that will automate the above demonstrated analyses