Self-Consistent Bootstrap Current in QOS Configurations

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THE BOOTSTRAP CURRENT IS A CRITICAL FEATURE OF STELLARATOR DESIGN AND OPERATION

- **The bootstrap current affects plasma properties at a fundamental level with changes in:**
  - **equilibrium**
    - » **transform, shifts, surface quality, etc.,**
  - **stability**
    - » **ballooning, kink, and resistive modes.**
- **Operationally, it is difficult to control because:**
  - **the total current is roughly proportional to plasma pressure and the profile is sensitive to the configuration,**
  - **the collisionallity regime is important,**
  - **current response to changes is on the L/R time scale.**

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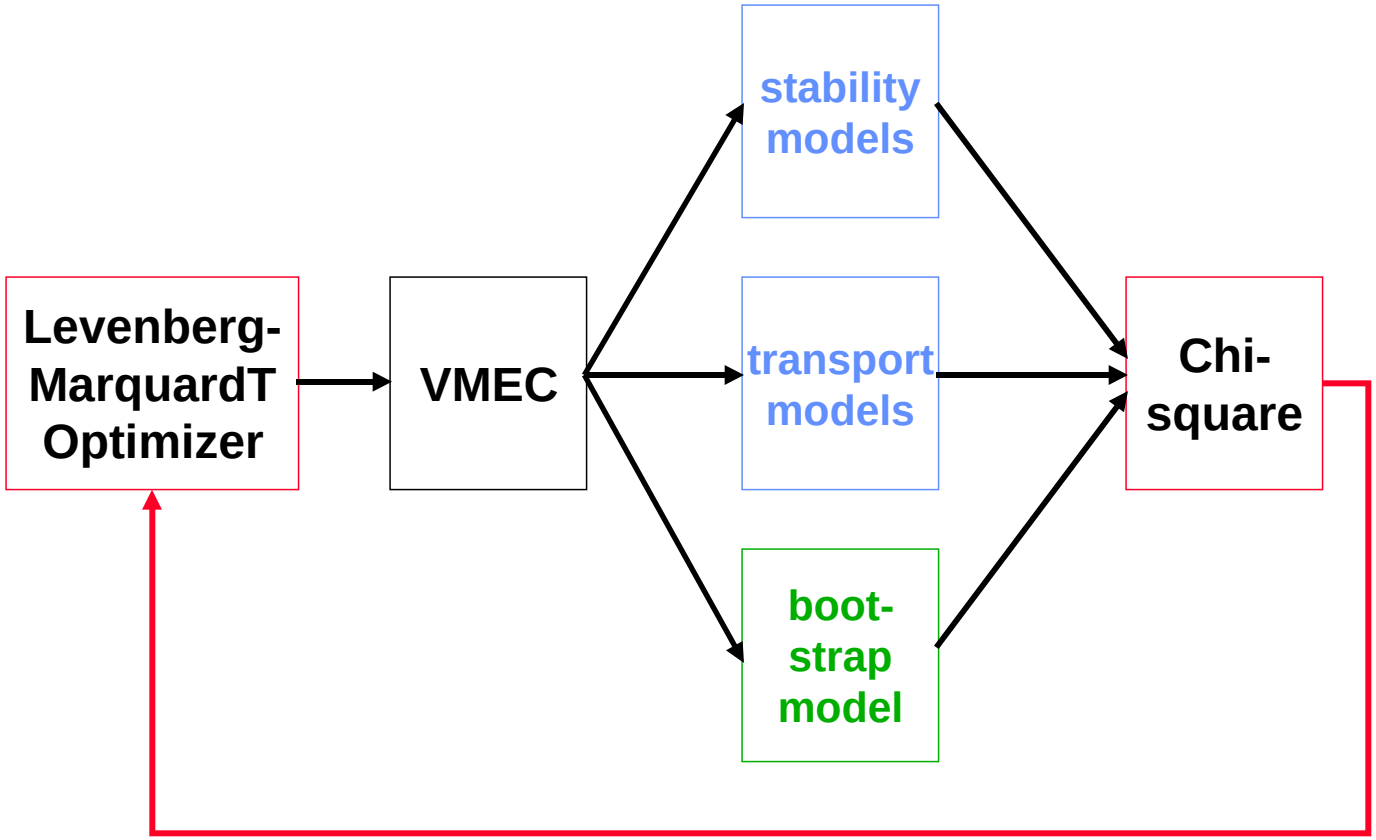
THE BOOTSTRAP CURRENT HAS BEEN ADDED TO THE THE STELLARATOR OPTIMIZATION CODE AS A NEW “TARGET”



TOPICS

- Description of bootstrap model
- Sensitivity to:
  - magnetic resonances,
  - collisionality,
  - profiles
- Examples of optimization process

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BOOTSTRAP MODEL

- For use in optimization, an evaluation needs to be computationally efficient--less than about 10 s per evaluation.
- A number of finite collisionality models are available:
  - DKES, delta-f, NIF.
- However, their run time is, at least for the present, too long.
- Thus a collision<u>less</u> analytical model K. C. Shaing et al., Phys. Fluids B 1, 148 (1989) and Phys. Fluids B 1, 1663 (1989), was used.

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IMPROVEMENTS WERE MADE IN THE COMPUTATIONAL EFFICIENCY IN ORDER TO HAVE MINIMUM IMPACT ON THE OVERALL TIME FOR AN OPTIMIZATION CYCLE

- **The analytic model was reformulated in terms of flux surface averages with appropriate metrics:**
  - **for Boozer coordinates, number of terms was reduced by a factor of two,**
  - **convergence with number of modes was improved by over a factor of two.**
- **Field line integrals were optimized with a factor of two improvement.**

The net result was a reduction in run time by (typically) 10-20.

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RESONANCES, COLLISIONALITY, AND PROFILES MODIFY THE BOOTSTRAP RESPONSE

- **Magnetic differential equations are solved to obtain the bootstrap current. Thus there are resonant terms of the form:**

$$\frac{1}{m - qn}.$$

Their impact is minimized by using a phenomenological broadening.

- **Low collisionalities are required to observe a fully developed bootstrap current, e.g.,**

$$J_{bs} \alpha \frac{1}{1 + \sqrt{\upsilon^*}}.$$

- **The bootstrap current depends on the relative contributions of temperature and density to the pressure gradient.**

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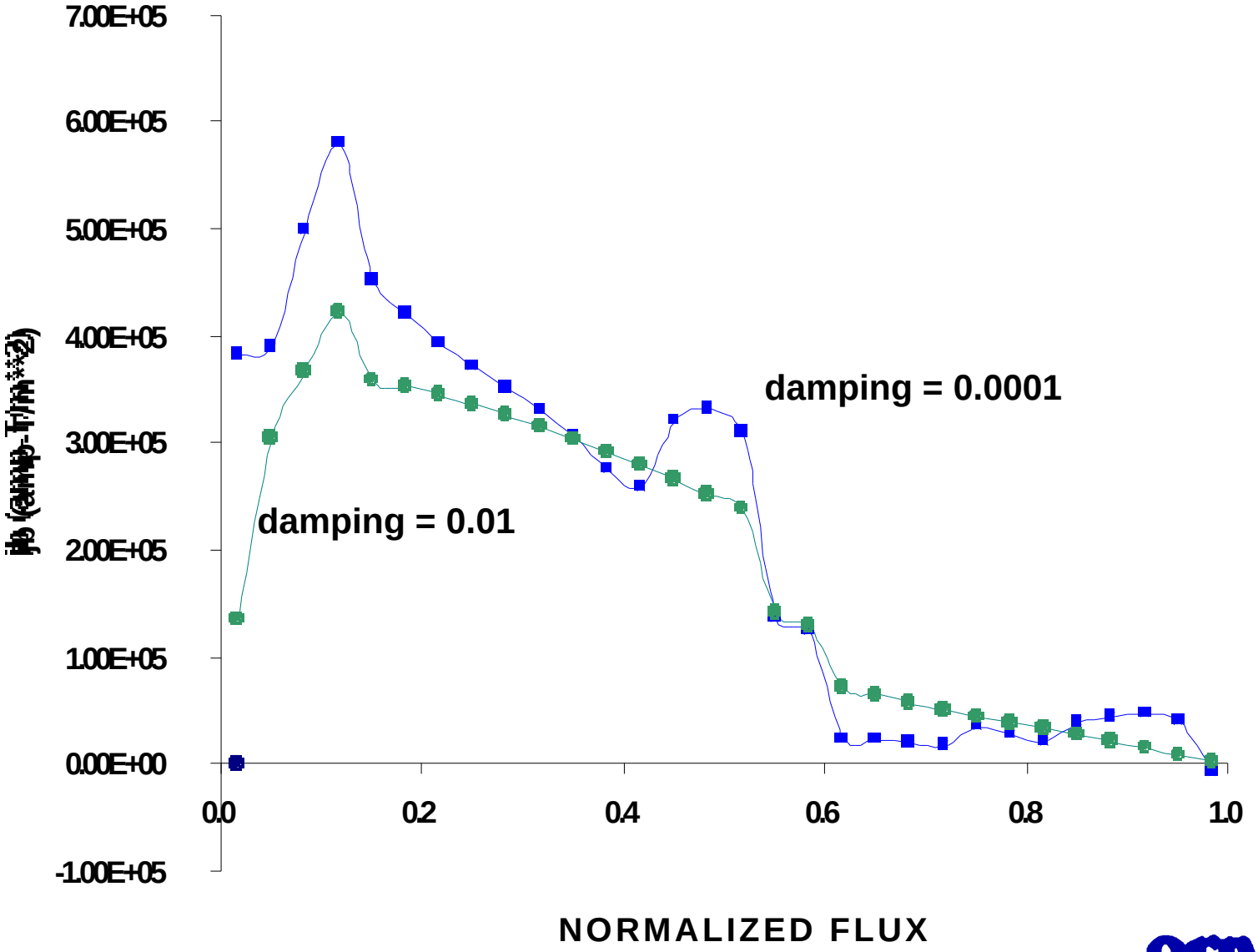
A PHENOMENOLOGICAL BROADENING IS USED TO SMOOTH THE RESONANCES



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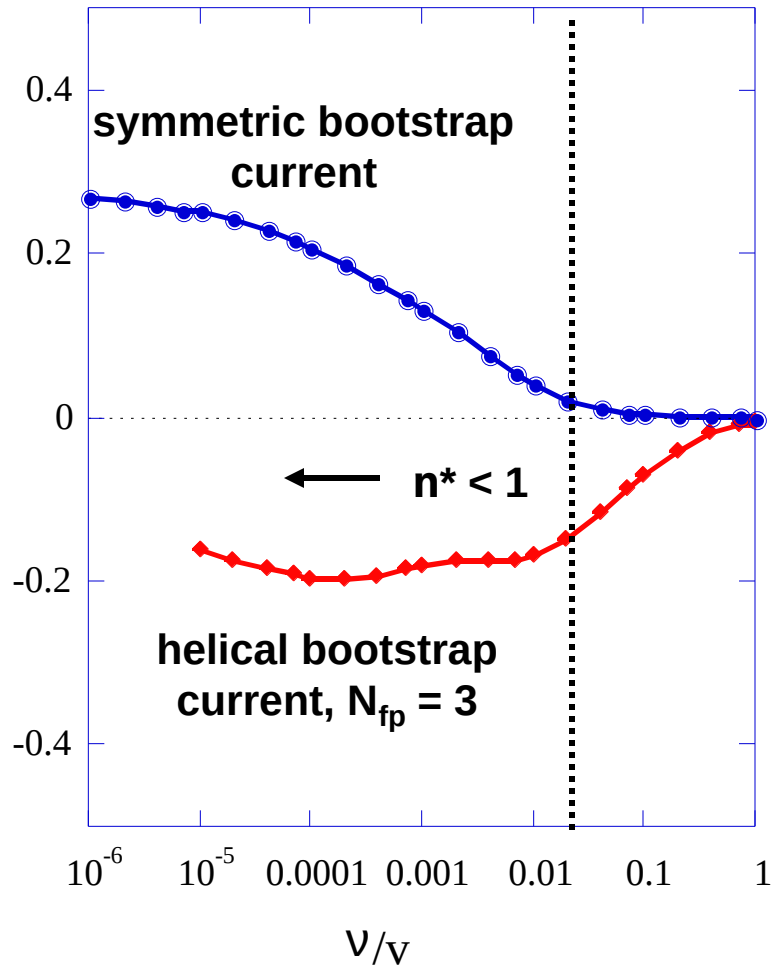
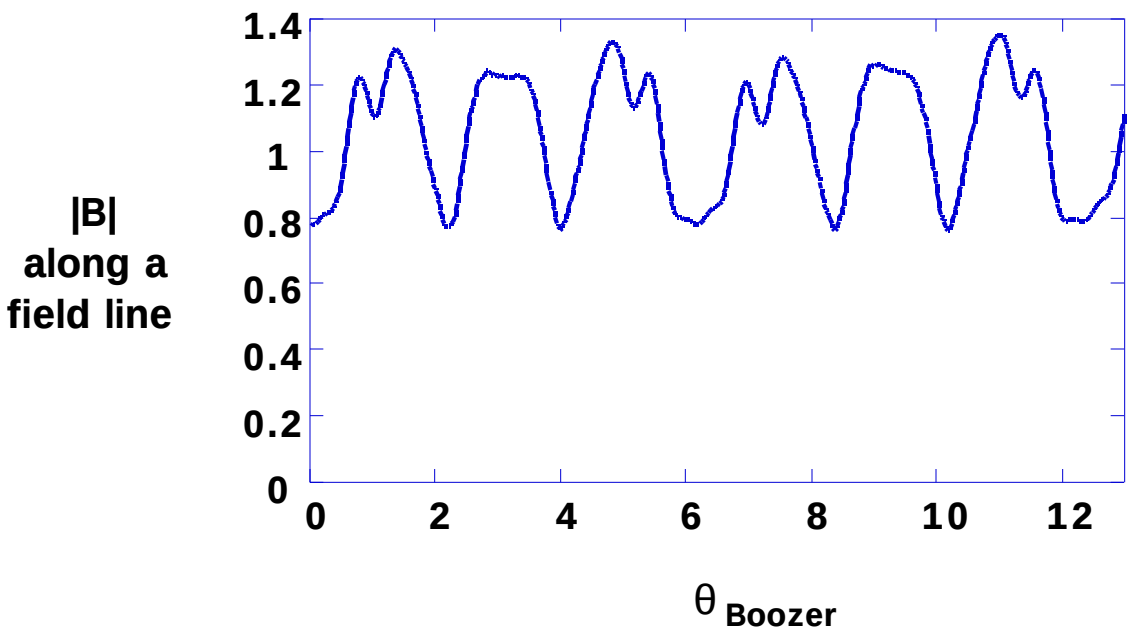
BOOTSTRAP CURRENTS ARE SIGNIFICANT AT HIGHER COLLISIONALITIES FOR CONFIGURATIONS WITH A STRONG HELICAL COMPONENT

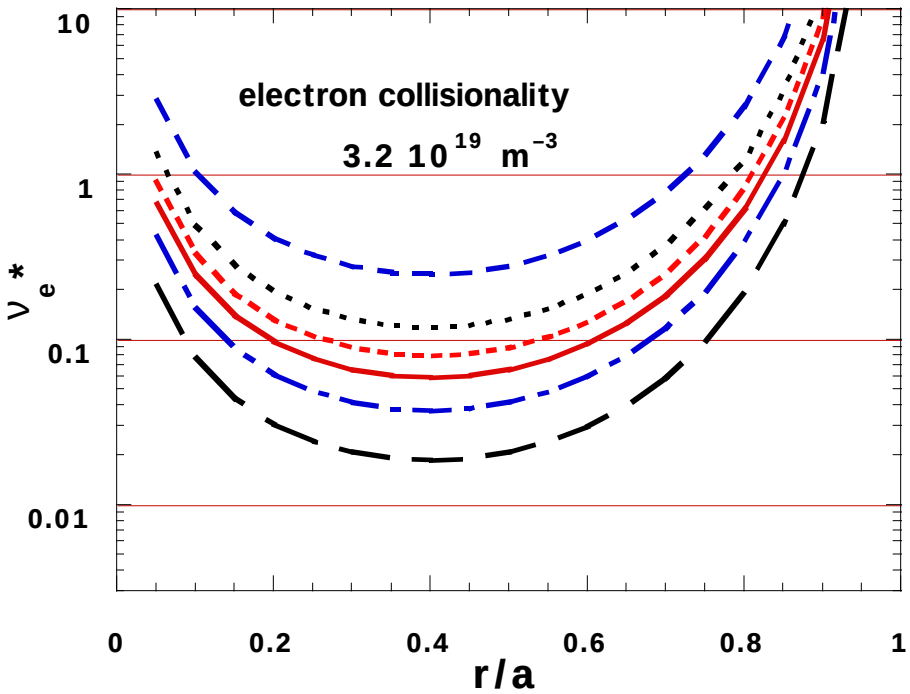
The pressure driven parallel particle flux, Γ_{31}, is estimated by DKES as a function of ν/v . The current is an integral over Γ_{31} velocity with an appropriate weighting, but ν/v of ~0.02 corresponds roughly to ν^* of 1.

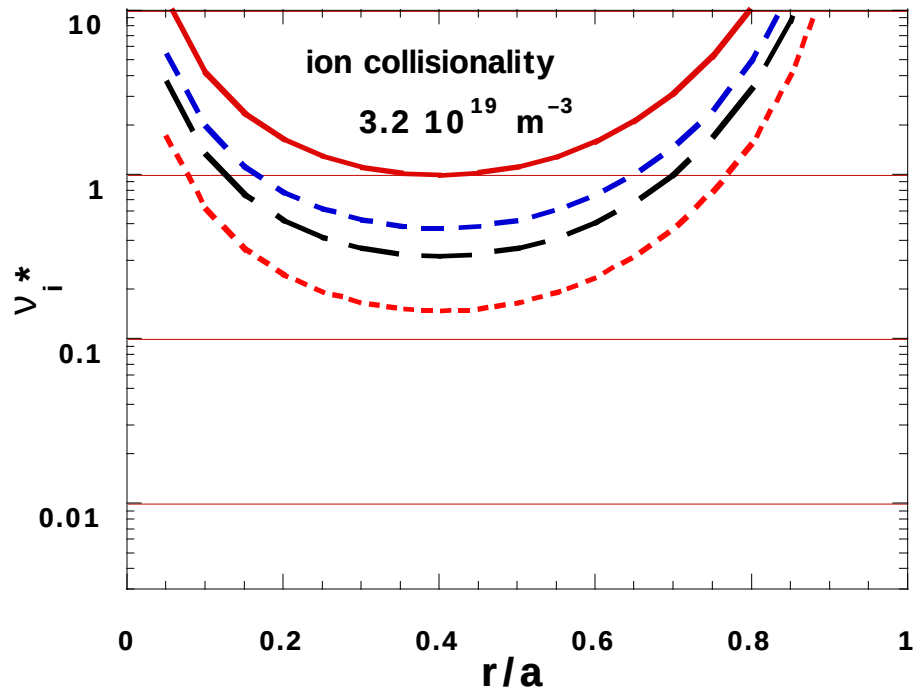


THE DOMINANT MAGNETIC FEATURE FOR A TYPICAL QOS IS THE HELICAL RIPPLE



THE RANGE OF ROUGHLY CONSTANT BOOTSTRAP CURRENTS OVERLAPS THE COLLISIONALITIES EXPECTED IN A “CONCEPT EXPLORATION” EXPERIMENT





However, attaining moderate collisionality at the higher densities that characterize higher beta levels depends on details.

BOOTSTRAP CURRENT IS SENSITIVE TO BOTH TEMPERATURE RATIO AND RELATIVE TEMPERATURE AND DENSITY GRADIENTS

T_e/T_i T^{α} P^{α}	0.5	1.0	2.0
0.25	70.7	71.7	72.9
0.50	56.7	59.1	61.4
0.75	42.9	46.4	50.0

Bootstrap current (I•B/B, kA) for varying temperature ratios and profile factors

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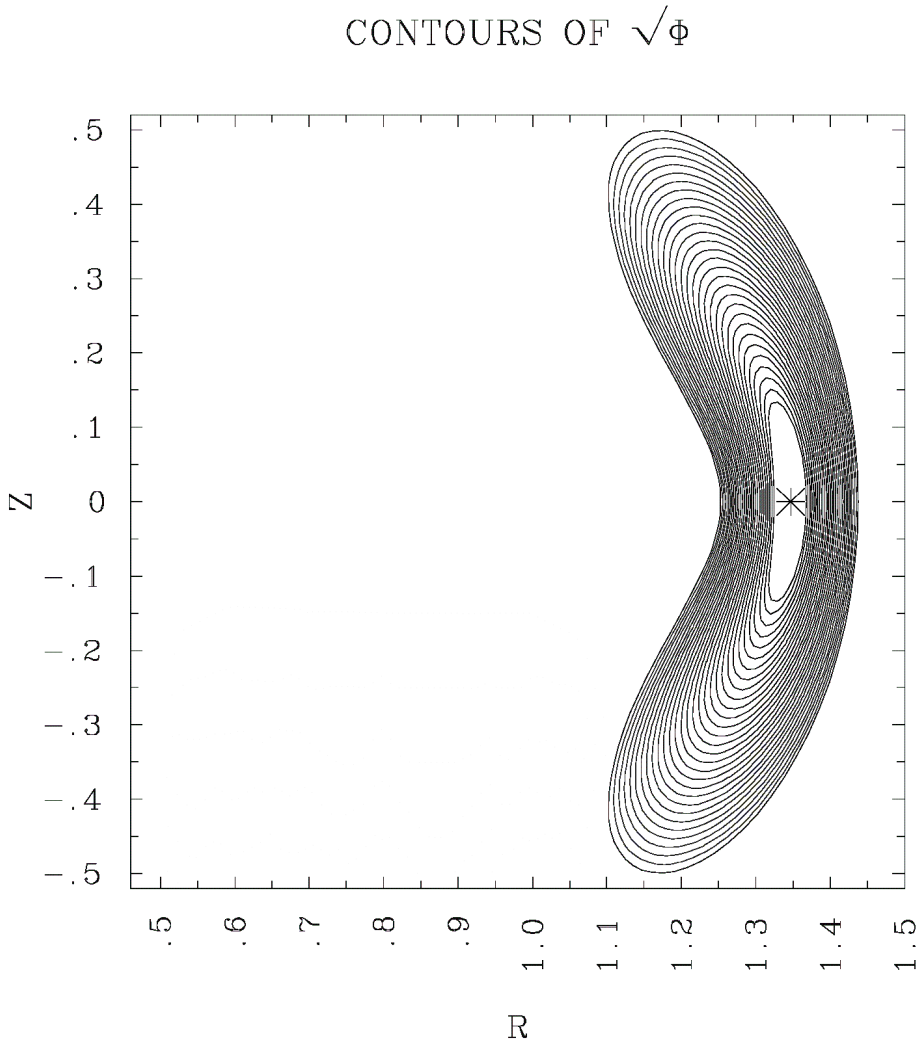
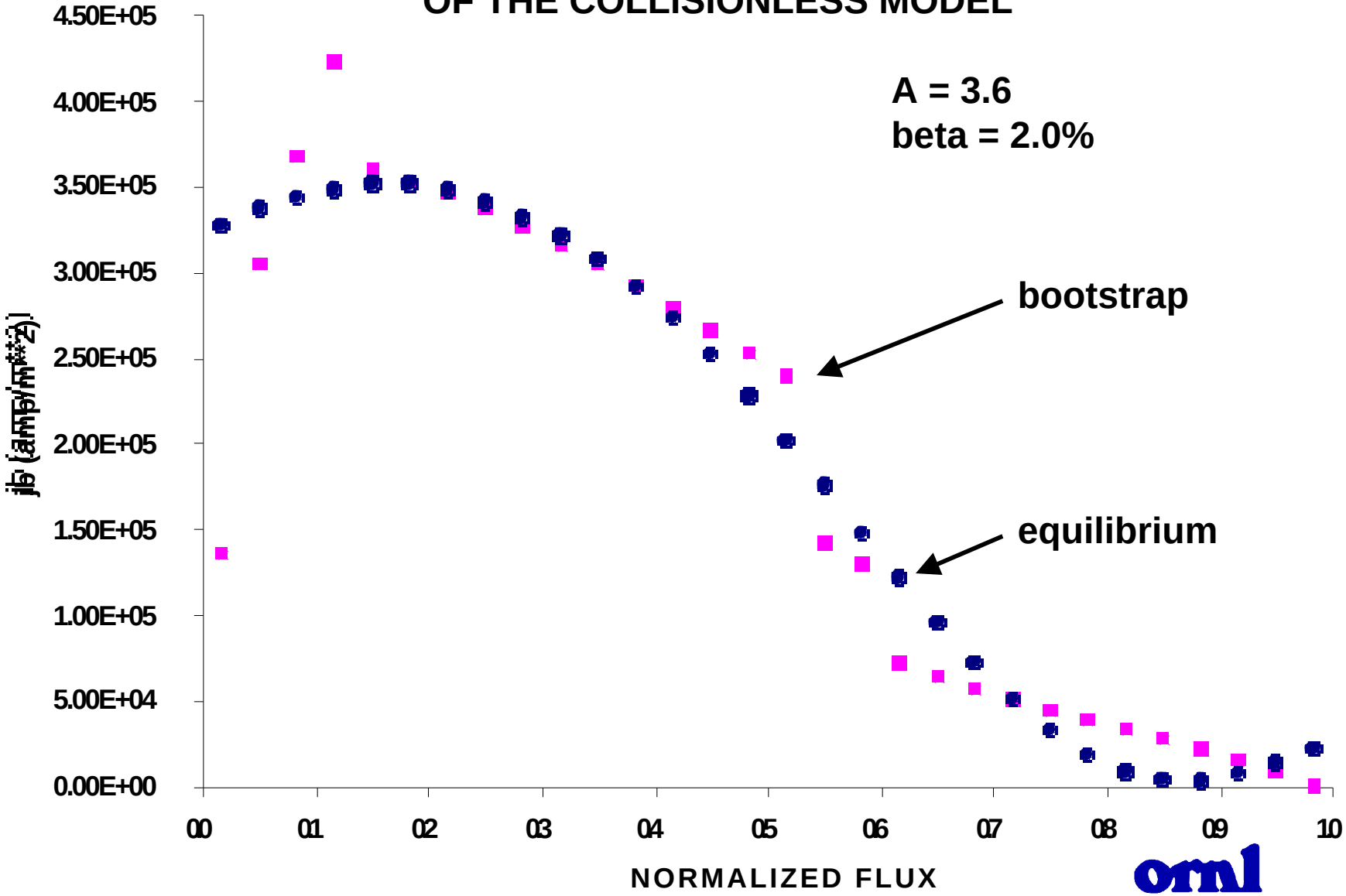
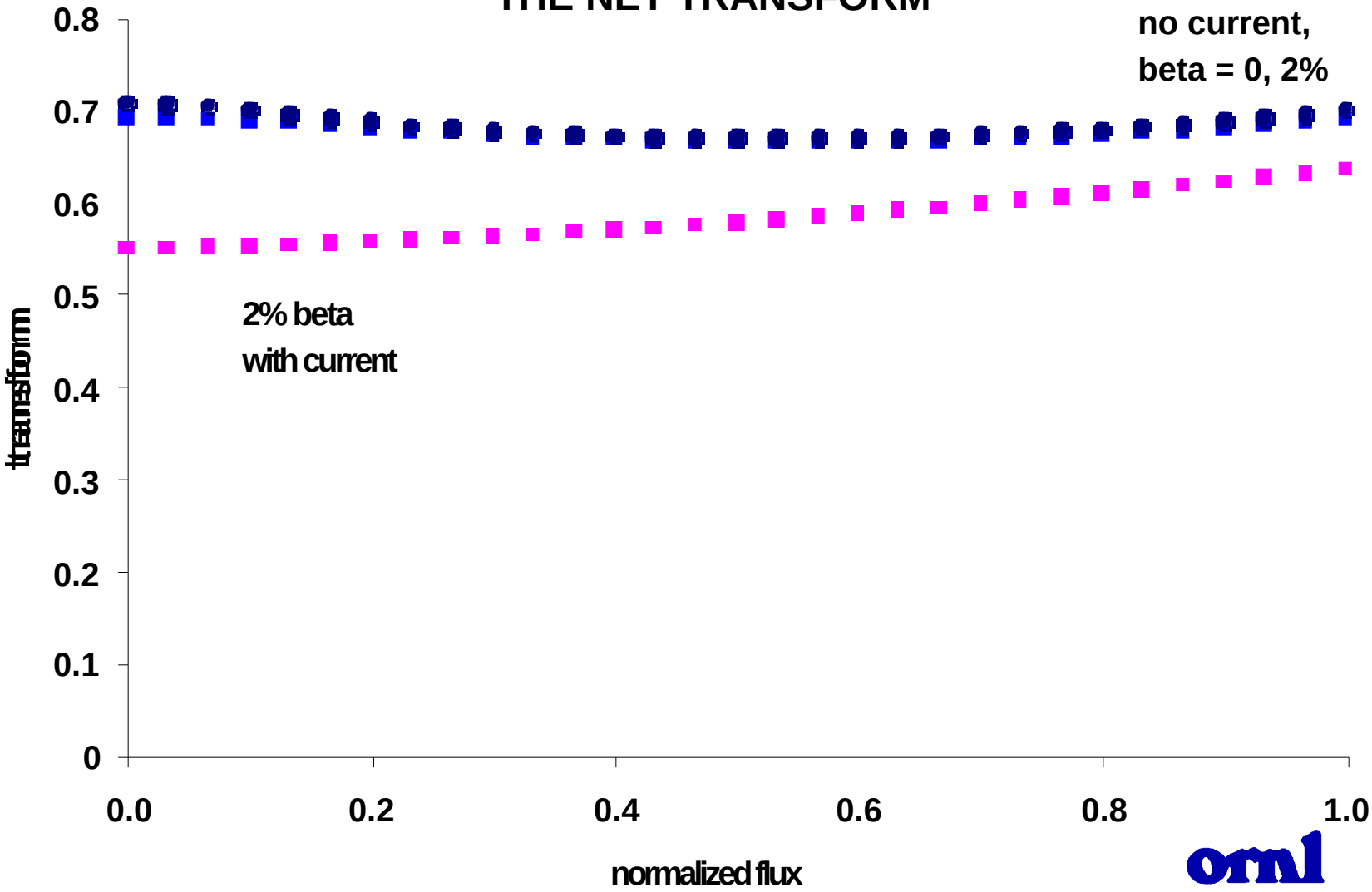
AN ASPECT RATIO 3.6 WITH A BALLOONING STABLE BETA OF 2% WAS ONE RESULT OF THE OPTIMIZATION PROCESS



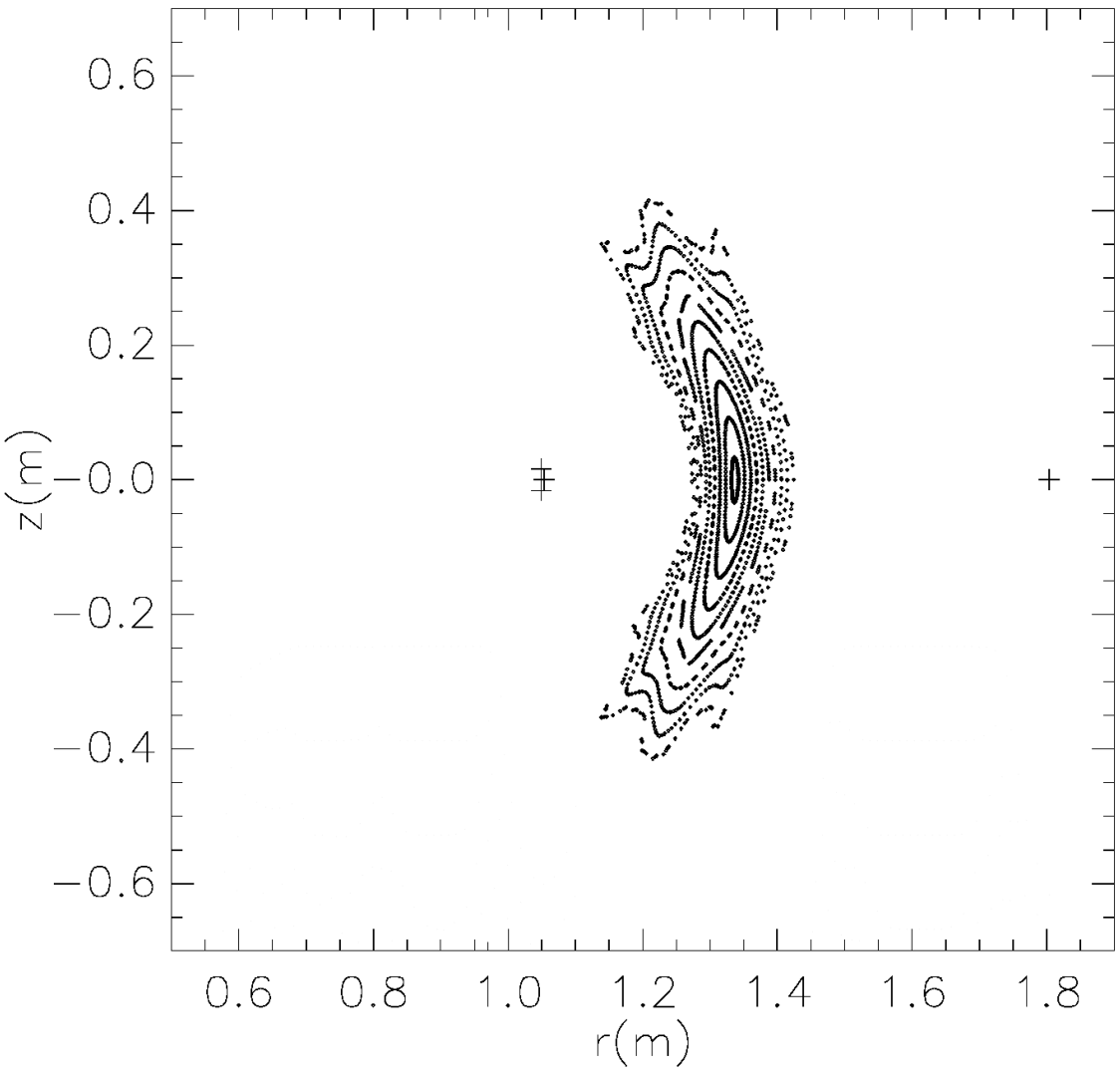
FOR MANY CASES, BOOTSTRAP AND EQUILIBRIUM CURRENTS ARE CONSISTENT WITHIN THE UNCERTAINTIES OF THE COLLISIONLESS MODEL



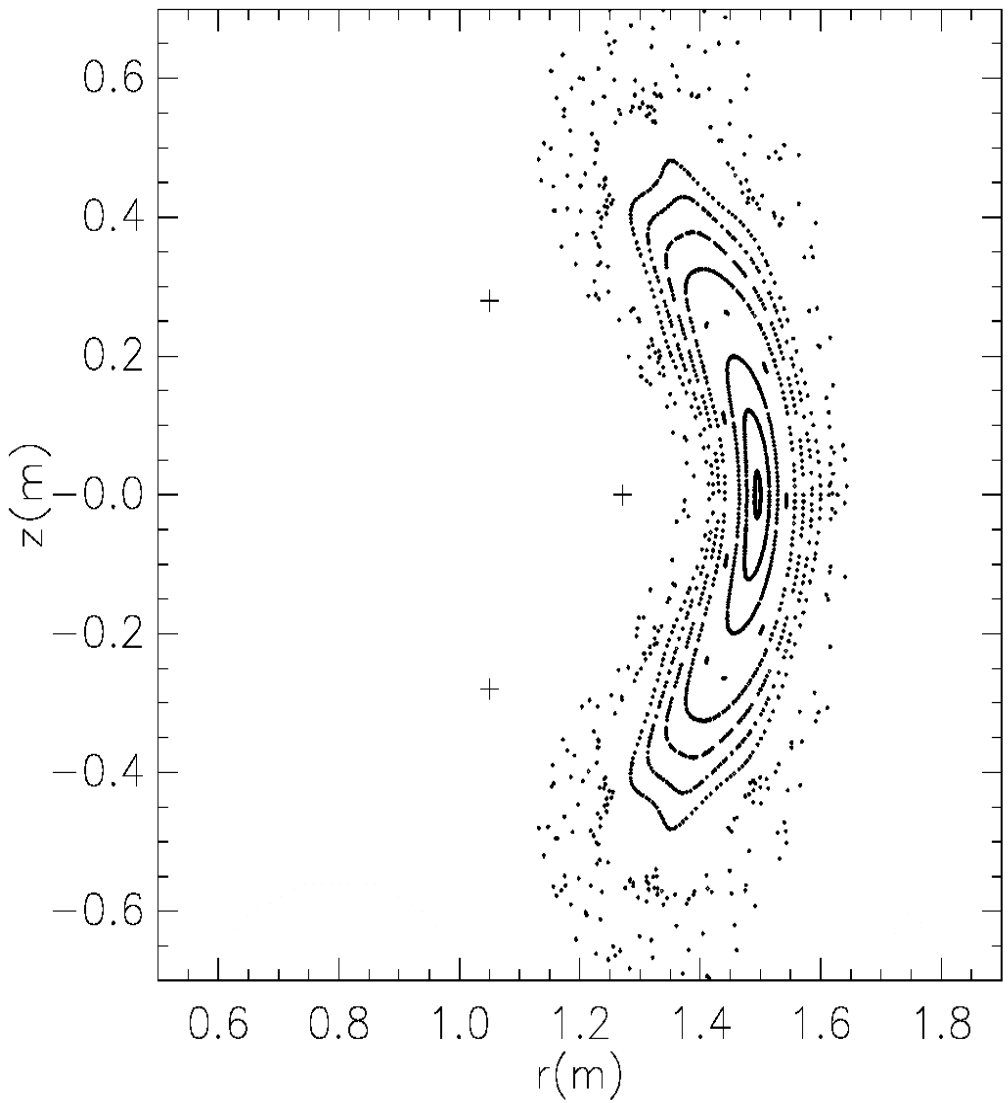
THE BOOTSTRAP CURRENT CONTRIBUTES ABOUT 10% OF THE NET TRANSFORM



FLUX SURFACES BASED ON CRUDE COILS (2% RMS B ERROR) SUGGEST THAT STARTUP FROM THE VACUUM SHOULD BE POSSIBLE



COILS WITH A 1% ERROR REDUCE THE OUTER ISLANDS (NOT A BOOTSTRAP SELF CONSISTENT CASE)



SUMMARY

- **A computationally efficient model for the bootstrap current** has **been added to the stellarator optimization code. Model uncertainties are at the several 10s of percent level.**
- **Cases with self consistent bootstrap currents and interesting stability properties, β = 2-3% for initial optimizations, have been developed.**
- **For these cases:**
  - **the bootstrap current tends to be in the negative (compared to a tokamak) direction,**
  - **10-20% of the transform results for bootstrap currents,**
  - **vacuum surfaces for even "poor" coils are reasonable.**

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