Design, Fabrication, Installation and First Results of the HBT-EP Shaping Coil

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1 Abstract

A low self-and-mutual inductance, zero net turn coil and its capacitive power supply have been fabricated and installed on the HBT-EP Tokamak. The coil will locally shape HBT-EP's normal circular cross section, up to and including the creation of a poloidal field null above the inboard midplane. This will enable HBT-EPs first investigation of the effects of shaping on the MHD multimode spectrum. Post installation tests have affirmatively proven the ability of the coil to impose a continuum of shaping, from circular to fully diverted. A description of the coil system, it's components, and qualifying tests are below. Results of initial experiments with are also provided and compared with simulations.

2 Motivation

- Simulations of shaped and unshaped plasmas using TokaMac and DCON show change in expected resonant plasma modes
- MHD multimode response shows decoupling of multimode effects with shaping.

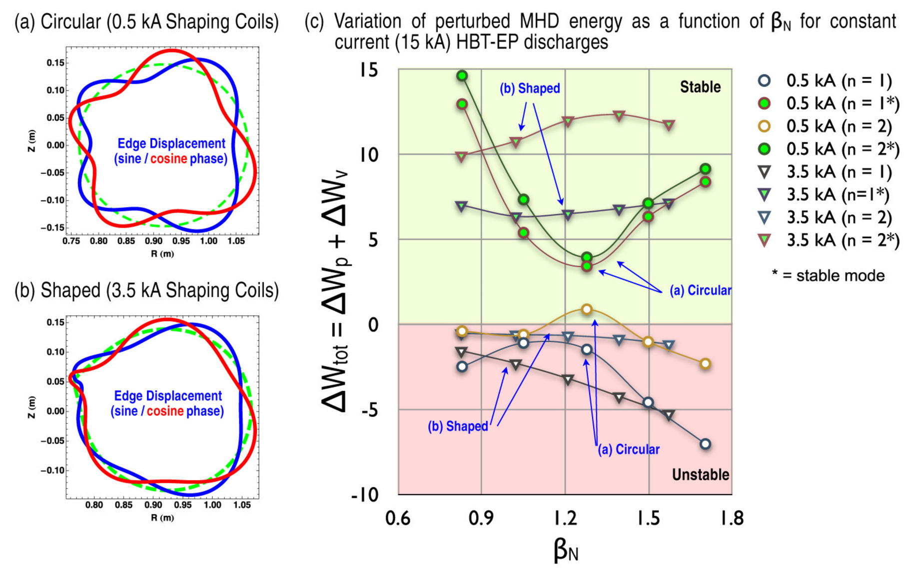

Fig. 1
Unstable and "most marginal" modes modeled in DCON for n = 1 and n = 2 in circular and shaped plasmas.

- There is a strong multimode response across all modes for the unshaped plasma when β_n rises past 1.2 (correlates to q_a=3). Beta was scanned by taking a typical HBT-EP plasma equilibria and varying the core pressure[1]

3 Design and Fabrication

3.1 The Coil

- The HBT-EP shaping coil provides up to 40kA-turns of current. HBT-EP's usual I_{plasma} is 10-15kA
- The coil consists of a single 1/0 welding wire, wound toroidally 8 times. It is located slightly above the high field side midplane.
- The 8 loops are distributed into 3 bundles, consisting of 2, 4, and 2 windings.
- The winding reverses direction twice, such that the central 4-loop bundle carries current in thhe opposite direction from the flanking 2-loop bundles.
- Zero-Net-Turns design reduces coil self (L) and mutual (M) inductance
- Low L allows fast turn on, and high-current operation with low energies
- Low M reduces the shaping coil's interference with existing magnetics, and localizes the plasma shaping to a few poloidal degrees from coil center.

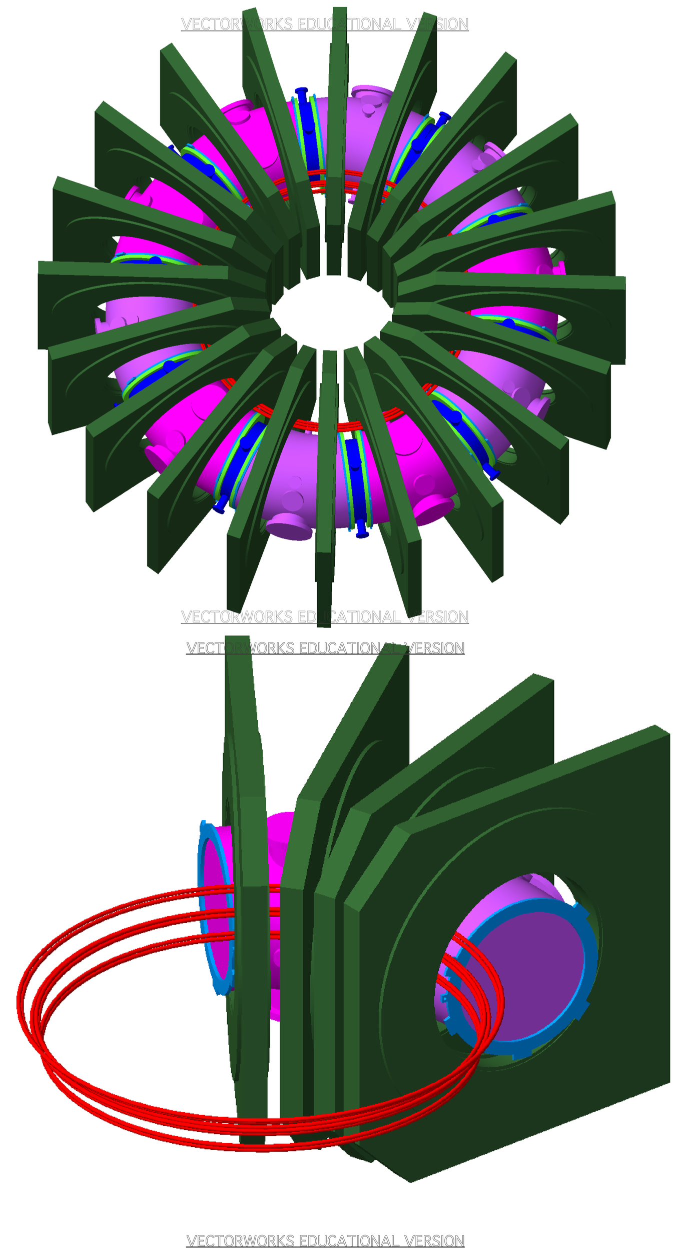

Fig. 2
Full and sectioned views of the HBT-EP Tokamak with the new shaping coil installed

- The coil's low inductance (42μH) and low resistance(<50mΩ) allow for the use of a low energy, low voltage power supply.

3.2 The Power Supply

- The shaping fields are sustained by capacitive discharge, provided by a 900V, 7.5mF startup bank, and a 250V, 0.6F crowbar bank.
- The capacitors are fired in two-stages, the start bank providing a quick establishment (850μs) and the crowbar bank long sustainment (90% of max current after 6ms) of the shaping field.

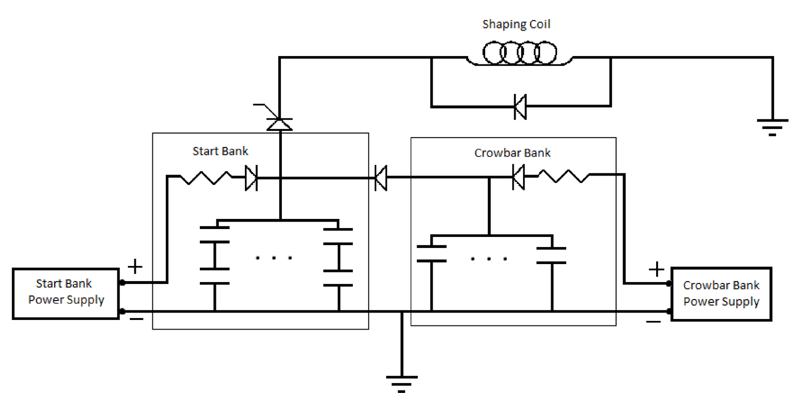

Fig. 3
Diagram of the HBT-EP shaping circuit.
Start bank is high voltage, fast risetime.
Crowbar bank is low voltage, high capacitance.

- The power supply provides up to 40kA-turns of shaping current with only 22kJ of energy thanks to impedance minimizing design.
- The crowbar bank is passively soft-switched into the circuit using a high current rectifier, making a smooth transition from start-up to steady-state regimes

Fig. 4
The HBT-EP shaping power supply
Start bank caps are blue, crowbar bank caps are white
Low required operating energy allows for compact construction

3.3 The Limiter

- HBT-EP has two poloidally complete Mirnov coil arrays (see Fig.'s 6 and 7 for location)
- Diverted plasmas will release significant energy to the area near the x-point.
- HBT-EP's existing limiters were designed for a circular plasma, they limit at the midplane and top/bottom of the plasma
- Two divertors were installed near the poloidal arrays to shade the sensors from incoming plasma

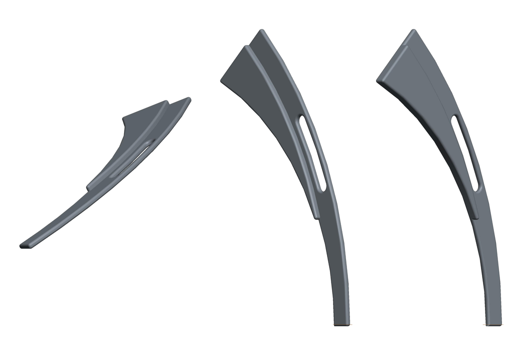

Fig. 5
The limiters are 1/4" 3-16 Stainless Steel
They shield 45° of poloidal angle, rising from the inboard midplane.

4 Operation and Qualification

4.1 SPICE Simulations

- Pulse amplitude and shape are controlled by the voltages on each bank; allows control of startup speed, tracking of shaping current to plasma current and/or position, and degree of plasma shaping - up to and including a fully diverted discharge.
- Voltages and capacitances selected in design phase via SPICE to allow a maximum shaping current of 9kA/turn

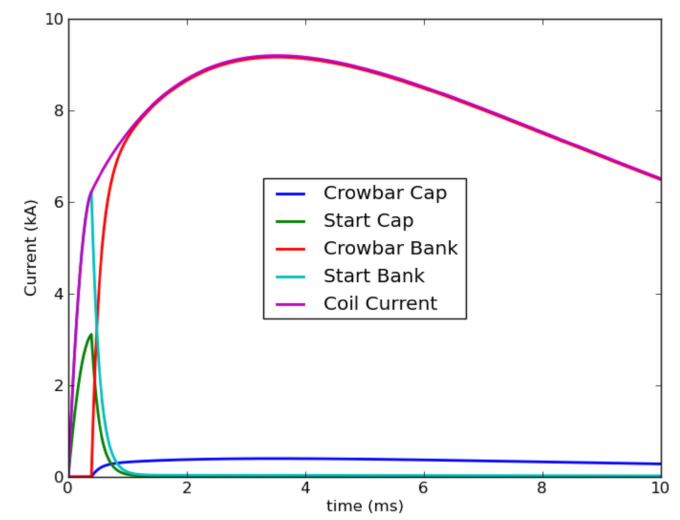

Fig. 6
SPICE simulation of cap bank discharge at maximum voltage
Passive switching allows smooth transition to crowbarred operation

4.2 Post Construction

- Shaping current is monitored by means of a rogowski coil manufactured in-house.
- Comparison of simulated pulse traces to actual operation shows higher current than expected.
- Design points of coil were 49μH, 22mΩ. Inductance measured @ 42 μH, resistance of but 17-18mΩ can be inferred from pulse shape.
- Transition from startup to crowbar operation is bumpier than predicted, but still much smoother than possible with active switching

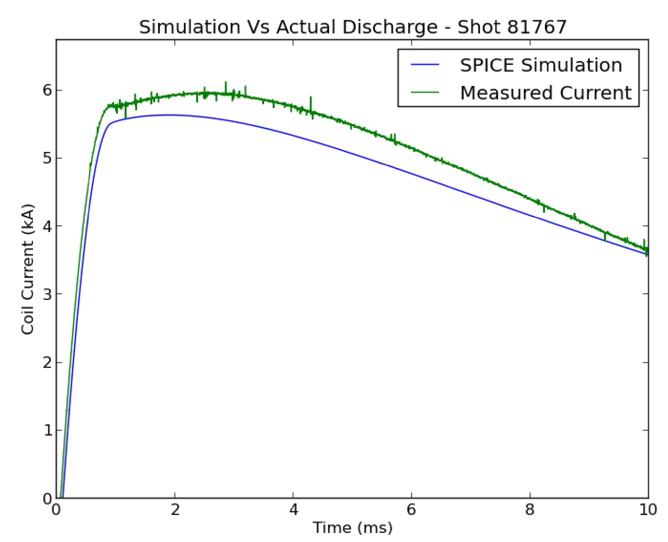

Fig. 7
SPICE simulation of standard discharge compared to current as meaured in the coil

Modeling of flux surfaces suggests HBT-EP has been successfully run diverted, at 70% power

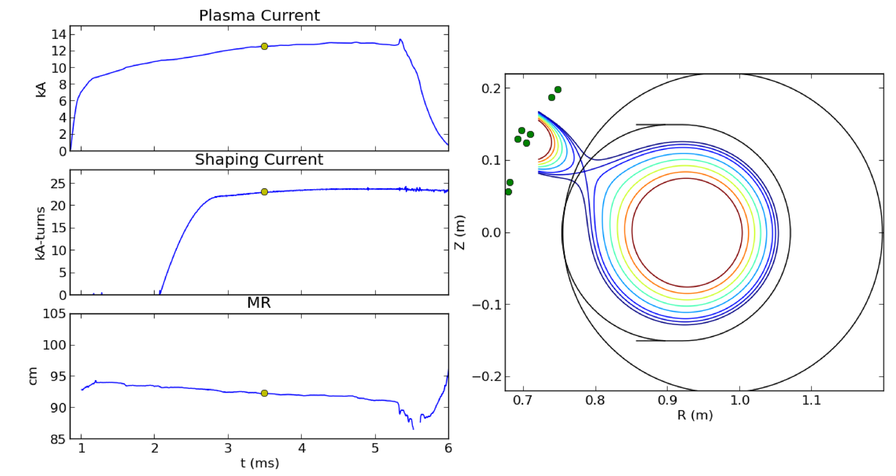

Fig. 8
Filament-current flux surface reconstruction using data from HBT-EP shot 81597
Black lines represent vacuum chamber and poloidal sensor array/plasma limiting surface
Green dots represent physical location of shping coil turns

- Toroidal non-axisymmetries are presentunavoidable due to high density of pre-existing diagnostics in the coil path.

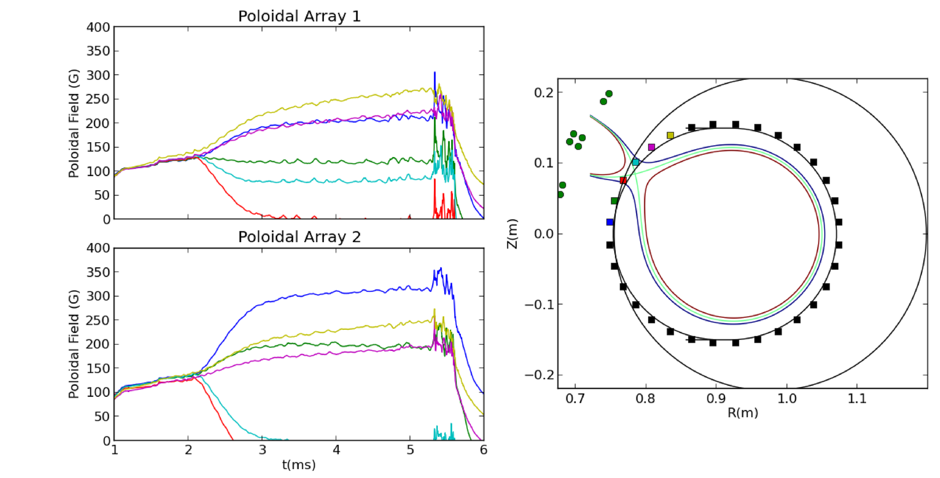

Fig. 9
Poloidal field measured at two toroidal locations near HBT-EP x-point for shot 81597.
B_p traces are color coded to the sensors as shown on the right.

5 Future Work

- Investigate the multimode spectum of shaped HBT-EP plasmas, specifically the effects of degree of shaping on MHD modes.
- Characterize and understand the cause of these differences, and extrapolate to the performance of advanced Tokamaks such as ITER or DEMO

6 Summary

- A shaping coil has been installed on HBT-EP, opening the door to diverted operation
- Low-Z design ensures the standard HBT-EP discharge in non-shaped plasmas is unaltered
- Test runs have demonstrated diverted operation to be within reach.

7 Acknowledgements

Design, fabrication and installation were all aided greatly by the contributions of Nick Rivera and James Andrello.
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References

[1] D. A. Maurer, *et. al.*, Plas. Phys. Control. Fusion, (2011) Vol. 53 Iss. 7