The Quasi-omnigeneous Approach to Compact Stellarators – a concept exploration device

D. B. Batchelor – ORNL

Collaborative programs with: Auburn University, University of Madrid, University of Montana, PPPL, University of Texas, University of Wisconsin

Proof of Principle Program Review

OFES

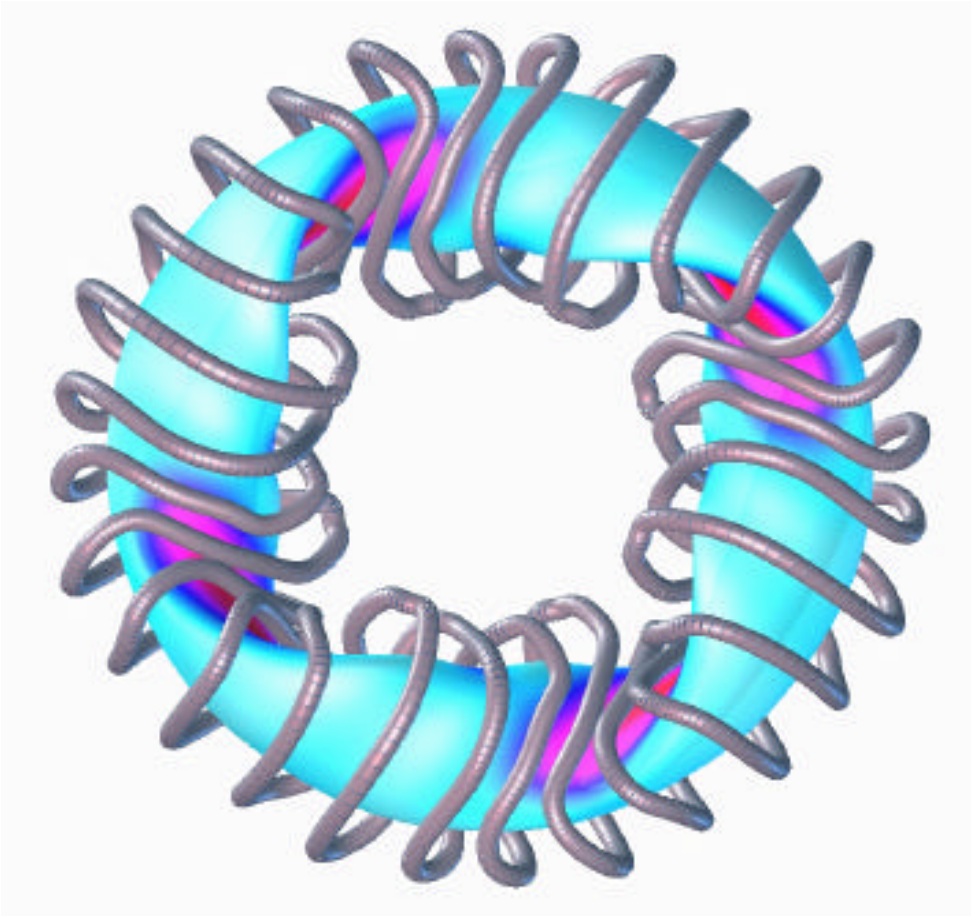
6-8-98

I. Potential of the Quasi-omnigeneous stellarator

II. Test of Quasi-omnigeneous stellarator at the concept exploration level

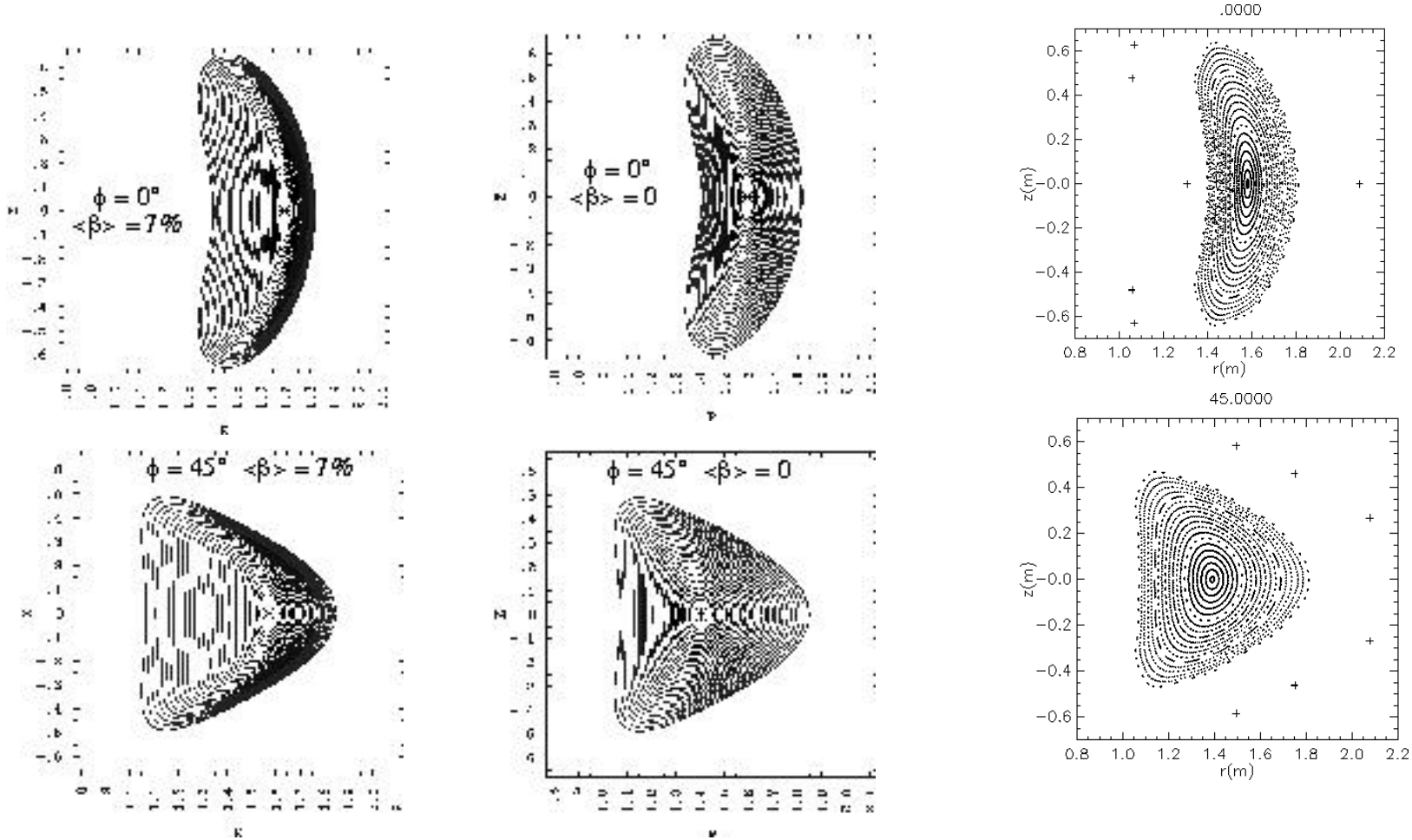
Optimization studies show exciting possibilities for QO compact stellarator

Four field period Quasi-Omnigeneous Stellarator ($R_0/\langle a\rangle = 3.6$) with modular coil set producing vacuum configuration



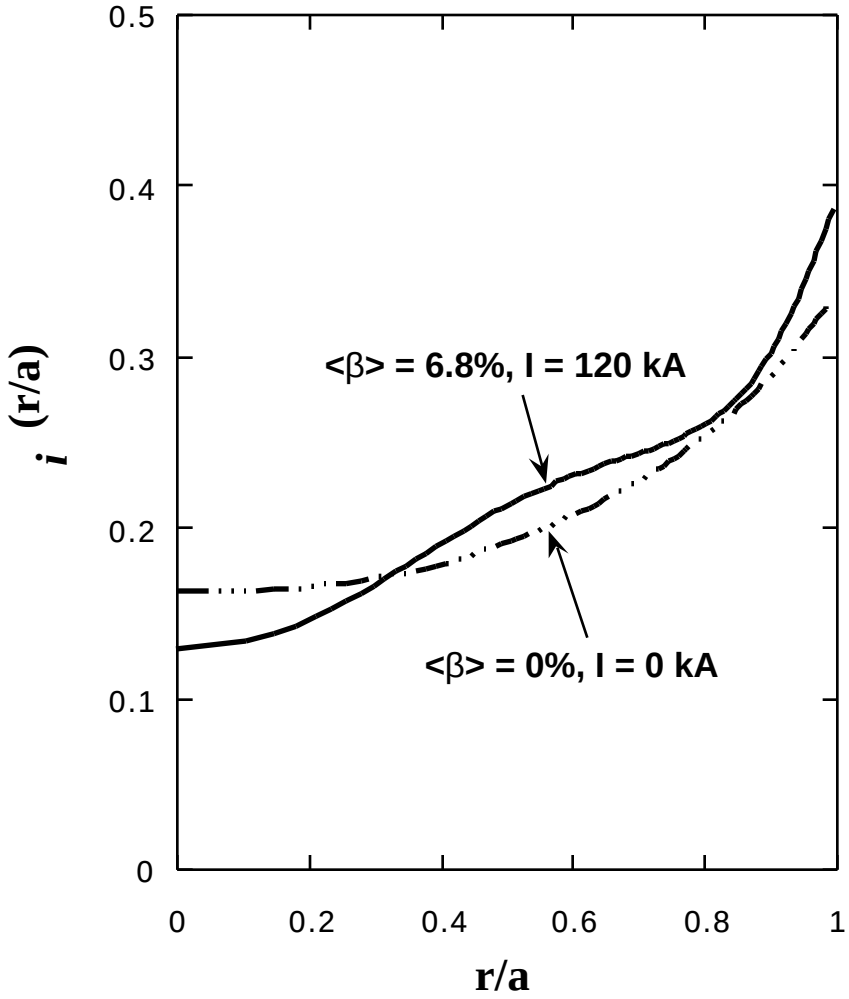
- **Mercier, high-n ballooning, and kink stable at $\langle\beta\rangle = 6.75\%$**
- **Good confinement**

Axis shift is modest as <β> is increased to 7% (fixed boundary)



- **Quite small, manageable islands in vacuum configuration reproduced by coils**

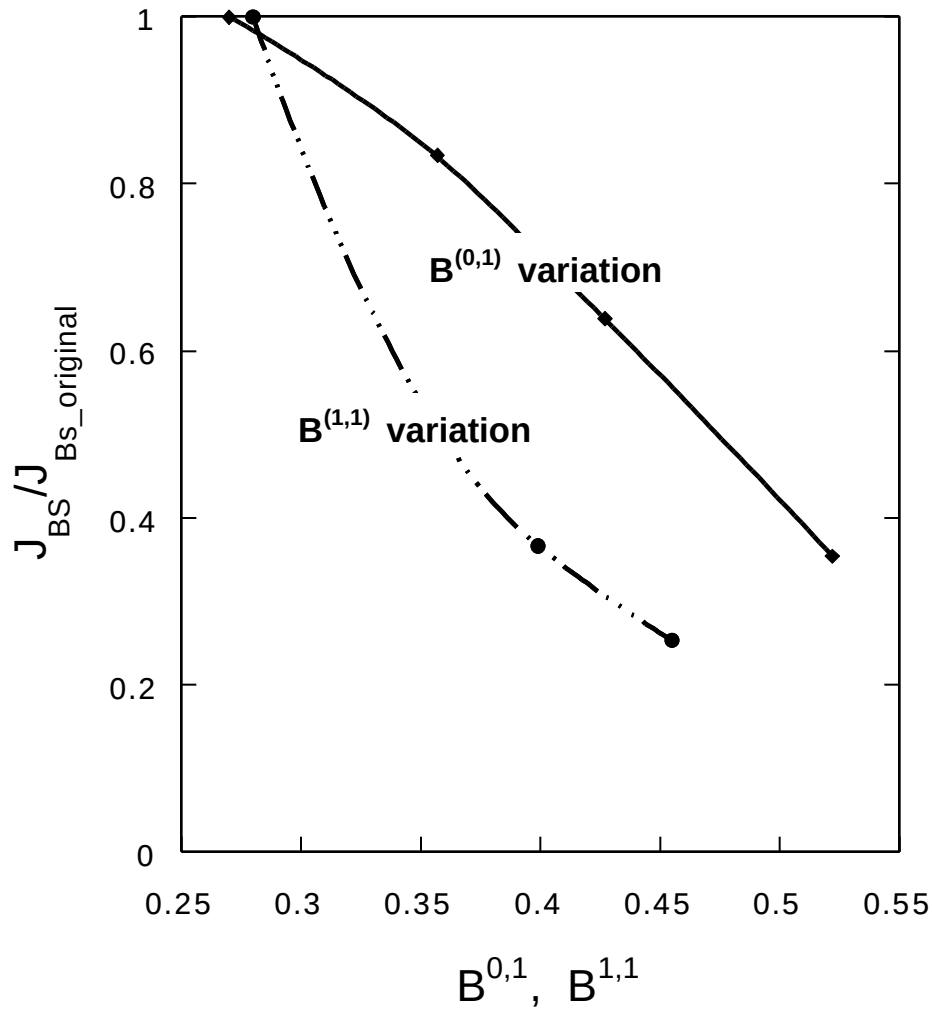
Variation of ι(r) is also modest as β is increased
(fixed boundary)



- Small change in ι avoids bringing in unwanted rational surfaces as β increases
- Provides confinement at startup
- Strong edge shear favorable for kink stability

Bootstrap current can be controlled by varying B_{mn} in QO devices: provides design and operational flexibility

Sequence of QO optimized configurations with additional target for specified $B^{(0,1)}$, $B^{(1,1)}$ in the optimization function



- **Inclusion of j_{BS} consistency with j_P inside optimization is under way**
- **Control of I_{BS} by plasma shaping demonstrated on ATF**

Transport and energetic orbit confinement have been estimated for intermediate experiment scale and reactor-sized devices

- **Monte-Carlo model:**
  - **Pitch angle and energy scattering**
  - **Flat T(r) and n(r) profiles**
  - **Test particle energy = $2xT_i$**
  - **Electric potential $e\varphi/T_i = 1$**

- **Results for intermediate scale device: R_0 = 1.5 m, B_0 = 1.4 T, I_P = 120 kA, T_e = 1.0 keV, $n_e = 5.0x10^{19}$ cm^{-3}**

τ_E = 50 msec or τ_E/τ_{ISS95} = 6.7

- **3.5 Mev alpha orbits have been examined starting at r = 0 and r/a = 0.5 over the full range of pitch angles ($-1 < v_{||}/v < 1$) for reactor scale device: R_0 = 10 m, B_0 = 5 T, T*e* = 10 keV, $n_e = 1.0x10^{20}$ cm^{-3}**

Prompt loss of 3.5 Mev alphas is ~10%

The reactor vision is similar for QO or QA

- **Smaller unit size**
  - **Low A**
  - **Tokamak levels of confinement**
- **Disruption elimination**
  - **Low I_P**
  - **Externally imposed rotational transform**
  - **Kink stabilization through plasma shape and ι profile control**
- **Low recirculating power**
  - **Elimination of current drive**
  - **Good confinement in vacuum configuration - ease of startup**
  - **Ease of control of operating point**

The design philosophy for QO approach is different from that for QA

- **Neoclassical confinement is optimized by approximately aligning particle drift surfaces with the magnetic surfaces, rather than relying on quasi-symmetry**
  - **Have obtained configurations having $\tau_{neoclassic}$ comparable to a tokamak and with excellent energetic particle confinement**
  - **There is no specific symmetry constraint on B_{mn} spectrum. Can adjust B_{mn} to control bootstrap current**
- **Maximize contribution to ι from external coils**
  - **Good confinement in vacuum – eases startup**
  - **Eases configuration control**
- **Reduce total plasma current**
  - **Reduce free energy due to I_P**
  - **Have found configurations with $I_{BS} = I_P << I_{tokamak}$**

We need to begin testing of the QO concept now to optimize design of second configuration in NCSX

To test the QO concept we must address:

- **Confinement of energetic particles in low-A, non-symmetric configurations**
- **Neoclassical transport optimization by Quasi-omnegeneity at low A**
- **Control of bootstrap current through external coils**
- **Reduction of anomalous transport in low-A, non-symmetric configurations**
- **Stability and disruptivity (ballooning and kink) in quasi-omnigeneous geometry**

Successful resolution of these issues will open a path for a compact, disruption free fusion concept

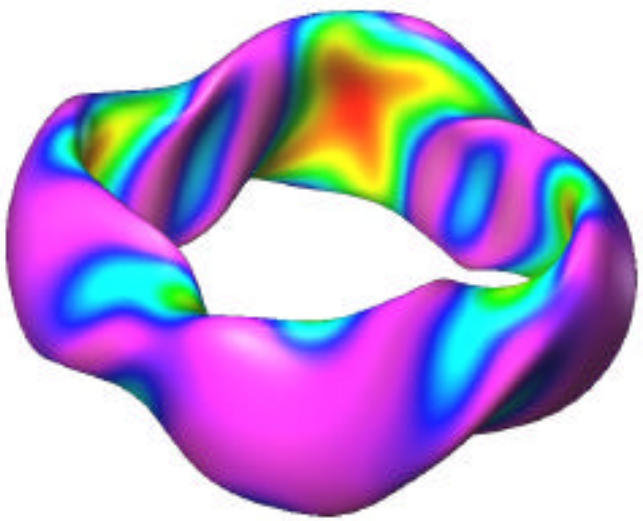
Anticipated characteristics for concept exploration scale Quasi-Omnigeneous Stellarator

R_0	1.0 m
$\langle a \rangle$	28 cm
$R_0/\langle a \rangle$	3.6
Volume	1.55 m^3
B_0	1 T
I_p	<150 kA
Pulse	0.2 - 1 s
Electron heating	0.4 MW; ECH - 53/60 GHz
Ion and electron heating	1 MW; ICRF

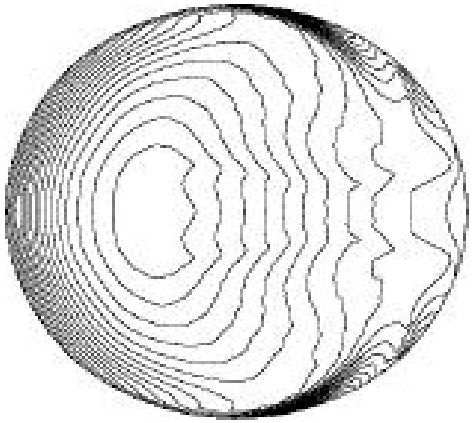
Flexibility for varying the magnetic configuration properties will be provided by auxiliary sets of coils, as on ATF and HSX

We have begun a program of optimization tailored specifically for a CE scale device:

- **Emphasized are:**
  - **Confinement of energetic deeply trapped particles (important for heating by ICRF)**
  - **Thermal particle neoclassical transport**



B_{min} contours



- **Monte Carlo code results give τ_E =10 msec with $e\varphi/T_i$ = 1**

Estimated QOS plasma parameters based on ISS95 stellarator scaling * with a confinement improvement factor H = 1 → 2

Plasma Parameter	0.4-MW ECH		1-MW ICRF	
n_e ($10^{19}m^{-3}$)	1.6[(a)]	3.2[(b)]	3.2	10
τ_E (ms)	6 → 11	8 → 6	5 → 9	9 → 17
β (%)	0.25 → 0.5	0.4 → 0.7	0.5 → 1.0	0.9 → 1.8
T_{e0} (keV)	1.1 → 2.3	0.8 → 1.6	0.8 → 1.6	0.4 → 0.7
T_{i0} (keV)	--	--	0.4 → 0.8	0.4 → 0.7
ν^*(min)	0.04 → 0.01	0.2 → 0.05	0.2 → 0.05	2.6 → 1.4

[(a)] 2nd harmonic X-mode

[(b)] O-X electron Bernstein wave mode conversion

$$\tau_E(\mathrm{ISS95}) = H \times 0.079 \langle a \rangle^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{0.4}$$

- H ≥ 2 is a program goal
- **H = 1.4 - 3 obtained in W7-AS**

QOS research program, tools and goals

Tools	Research Program	Program Goals
electron heating (ECH, ICRH)	bootstrap studies electron transport turbulence studies	Verify I_{BS} dependence on B_{mn} H factor ≥ 2
induced currents	kink stability disruption studies	delineate current driven stability limits
ion heating	Energetic particle conf. QO confinement opt. Finite β studies	confine ICRF tail demonstrate ion heating β > 1.5%
electric field (ECH, ICRH, induced current, pellets, biased probes)	transport barrier studies effects on neoclassical transport	H factor ≥ 2, β > 1.5%

Cost Profile for QOS Project (M$)

Fiscal Year	1999	2000	2001	2002	2003	2004	2005
Construction	0.5	1.1	1.8	2.1	1.0		
Operations	0.1	0.1	0.1	0.1	1.0	1.3	1.5
Enhancements		0.1	0.1	0.1	0.4	1.2	1.0
QOS Total	0.6	1.3	2.0	2.3	2.4	2.5	2.5

- Resources for preconceptual design not included
- The total project cost ($6.5 M, scaled from HSX costs) includes design, R&D, construction, site preparation, installation of 0.4 MW ECH, and a base set of diagnostics
- 3-4 years would be required for construction and commissioning after the final optimization and design phase
- Resources at ORNL, U Texas, and PPPL, PRC can be applied: heating systems, power supplies, control systems, utilities, diagnostics, computers, etc.
- Laboratory-university partnership, extensive collaborations, post-docs, and thesis students will be used in the program

Conclusions

- **Quasi-Omnegeniety offers great promise for a compact stellarator route to fusion.**

- **Exploring the physics of QO systems constitutes an essential element of the knowledge base needed to proceed to the proof of performance level of compact stellarators.**

- **A concept exploration scale QO experiment is needed now to begin developing the data base on low-A, QO stellarators and to provide an optimum design for the continuation of the NCSX program.**

- **We are ready to proceed with conceptual design of such an experiment.**