Experimental Stellarator Research at Columbia University

Francesco A. Volpe


with special thanks to:
CNT students: K.C. Hammond, A. Anichowski, R.R. Diaz-Pacheco, Y. Wei
CIRCUS students: B.Y. Israeli, J. Li, J. Mann, A. Clark, M. Doumet et al.
Former TARALLO collaborator: C. Caliri
Small university stellarators such as CNT can help answer questions relevant to larger ones

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- Do the coils need to be so complicated? Can we generate other 3D stellarator equilibria –besides heliac- with planar 2D coils?
- Can we include some tokamak’s advantages (easier construction, axisymmetry) in a stellarator or torsatron design?
- Do these new configurations generate or amplify rotational transform?

- Can we use stellarators in non-fusion basic research, e.g. to produce ions for accelerators?
CNT was built in 2002-2005 with DOE and NSF funding to confine non-neutral plasmas

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e$</td>
<td>$10^{12}$-$10^{14}$ m$^{-3}$</td>
</tr>
<tr>
<td>$T_e$</td>
<td>1-100 eV</td>
</tr>
<tr>
<td>$B$</td>
<td>0.01-0.2 T (typ)</td>
</tr>
<tr>
<td></td>
<td>0.3 T (max)</td>
</tr>
<tr>
<td>$R$</td>
<td>0.3 m</td>
</tr>
<tr>
<td>$a$</td>
<td>0.1 m</td>
</tr>
<tr>
<td>$V_p$</td>
<td>0.13 m$^3$</td>
</tr>
<tr>
<td>$P$</td>
<td>$&gt;10^{-10}$ Torr</td>
</tr>
</tbody>
</table>

Increasing pressure of neutrals $P$
increased degree of neutrality
up to quasi-neutral

[X. Sarasola, PPCF 2012]
CNT has some unique features in international stellarator scene

- Low aspect ratio, $A=1.9-2.7$
- Low $B<0.3T \rightarrow$ potential for relatively high $\beta$, provided sufficient $n_e$ and $T_e$ are reached?
  - High $\beta$ MHD at W7-AS [A. Weller]
  - Proposed high $\beta$ stellarator [H. Laqua]
  - High $\beta$ fits in tradition of Columbia. Comparison with HBT-EP?
- High fraction of trapped particles
  - ECCD: low Fisch- Boozer CD efficiency
  - Efficient Ohkawa CD
  - Trapped Electron Mode (TEM) turbulence?
- Movable IL coils
- Large vessel
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Error fields impact tokamaks and stellarators

- MHD stability
- Transport, confinement degradation
- Diagnostic alignment

To correct: fix existing coils or add compensation coils
In either case: need to understand causes
  - Numerical technique to identify CNT coil misalignments
  - If successful, could be applied to multiple EF sources in other devices
Flux surfaces are measured with an electron beam and a phosphor-coated rod.
Initial agreement between measured and predicted flux surfaces was poor.

\[ I_{IL}/I_{PF} = 3.68 \]

\[ I_{IL}/I_{PF} = 3.18 \]
Misalignments of the PF coils are measured with photogrammetry

- Markers placed on chamber and coils
- Software generates point cloud from relative positions of markers

- Result: PF coils as much as 40 mm off nominal position in some places
- Does not fully explain observed field error
Objective: deduce IL coil misalignments based on observed Poincaré cross sections

\( X(p) \) can be determined with a field line tracer

Finding \( p \) for a given \( X \) requires an iterative method
Define discrepancy vector: $F(p) = X(p) - X^*$

Newton step $\delta p$ satisfies $F = -J \delta p$

- Jacobian: $J_{ij} = \frac{\partial F_i}{\partial p_j}$
- $\delta p_1 \rightarrow p_1 = p_0 + \delta p_1 \rightarrow X(p_1) \rightarrow F(p_1) \rightarrow \delta p_2 \rightarrow \ldots$

Best linear unbiased estimator for $\delta p$:

- Minimize: $\chi^2 = \frac{1}{2} F \cdot C^{-1} F$
- $C_{ij} = \text{cov} (X_i, X_j)$
- $\delta p = (J^T C^{-1} J)^{-1} J^T C^{-1} p$
- Finite differencing interval must be sufficiently large

Use Newton-Raphson method to find $p^*$ such that $X(p^*) = X^*$
Verifications conducted using $X^*$ simulated from artificial displacements $p^*$

- Example: $p^*$ set to have IL1 displaced by 5 mm in the $z$ direction
- Reduction of $\chi^2$ by factor $>10^5$
IL coil displacements were optimized to fit experimental data for \( \text{IIL/IPF} = 3.68 \)

- PF coils assumed to be displaced according to photogrammetry
- All 10 IL parameters free
- Reduction of \( \chi^2 \) by factor > 100
Cross sections for optimized parameters exhibit significantly improved qualitative agreement.

\[ \frac{I_{II}}{I_{PF}} = 3.68 \]

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Onion-peeling concept

- Discrete layers of emissivity $e(\rho)$
- A layer contributes to pixel brightness $\rho$ in proportion to distance $L$ travelled by line-of-sight across layer
- $\rho = L e$
- $L$ from topology, $\rho$ from fast camera

$e \approx (L^T L)^{-1} L^T \rho$

$e_j$ = emissivity of $j$th layer
$L_{ij}$ = length of $i$th line-of-sight through $j$th layer
$\rho_i$ = brightness of $i$th pixel
Forward problem
Camera images were noise-subtracted
Images from glow discharges were inverted. Peak of emissivity moves with source.
Reconstructed images agree with experiment

(b) Processed image (3.3 cm)

(c) Reconstruction (3.3 cm)

(d) Processed image (5.7 cm)

(e) Reconstruction (5.7 cm)
Reconstructed images agree with experiment and emissivity peaks at edge of microwave plasmas, as expected.
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VMEC models how CNT equilibrium modifies with \( \beta \) and how coil-currents need to be changed.

- Effects expected on equilibrium and stability (mostly ballooning and Alfvén Eigenmodes).

\[ \beta = 0, \, 1.4\%, \, 3.7\%. \]

Fixed \( B_z \), fixed boundary.
1.) Densities determined by ECH cutoffs or radiative limits (for EBW heating) at 1 MW:

3.) $T_e$ then follows as $W/n_e V$:

2.) $\tau_e$ predicted by ISS95 scaling

$$\tau_e = 0.256 R^{0.65} a^{2.21} B^{0.83} n_e^{0.51} P^{-0.57} t_{uv}$$

4.) $\beta$ deduced from $T_e$ and $n$:
100 kW of EBW heating could lead to $\beta \approx 10\%$
Earlier ECRH system
- < 1 kW magnetron, 2.45 GHz, 60 Hz pulsed
- Launches from viewport on chamber wall
- Plasmas: $T_e \sim 5$ eV (nonthermal), $n_e \sim 10^{16}$ m\(^{-3}\)

Upgrade to:
- 10 kW magnetron, 2.45 GHz, CW
- Will launch through antenna near plasma edge

Motivation
- Higher power needed to study high-\(\beta\) plasmas
- 10 kW system is an intermediate step
Launch antenna was designed for simplicity and high first-pass absorption

- Circular waveguide; approaches plasma edge
- Interior held at atmosphere to avoid breakdown
- Enters obliquely through port
External waveguide system designed to allow arbitrary linear polarization of the electric field.
ECRH setup outside vessel

- magnetron head
- twist-flex
- taper

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
ECRH setup in-vessel

Waveguide launcher

IL coils
Magnetic axis was illuminated by emissive probe for ECRH alignment
Taper was rotated to align wave E parallel (O-mode) or perpendicular (X-mode) to plasma B.
First microwave plasmas made with the new ECRH system
3.5 kW plasma serendipitously 5x overdense

- FX-B mode conversion from LFS? SX-B from HFS?
- Improved impedance matching expected to lead to 10 kW coupled to plasmas $\rightarrow$ higher $T_e$
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Pure-electron plasmas

- Neutral pressure kept to $\sim 10^{-9}$ Torr
- Electrons emitted at axis would fill flux surfaces$^3$

Partially neutral and quasineutral plasmas

- Higher background pressures lead to greater ion concentrations$^4$
- At $\sim 10^{-5}$ Torr, plasma is essentially quasineutral

Synergies are observed when thermoelectrons and microwaves are used at the same time.

Reduce minimum $P_{\text{neutral}}$ for $\mu$-wave breakdown

- $\text{N}_2$: $6.5 \times 10^{-6}$ Torr → $\sim 2 \times 10^{-6}$ Torr
- Higher $T_e$ attainable (up to $\sim 20$ eV at lowest background pressures)

Increase attainable plasma density

- Effect intensifies with filament bias

![Graph showing electron density vs. probe displacement with different beam conditions](image)
NSTX-U uses multiple pre-ionization sources prior to Ohmic heating

- 28 GHz ECRH, thermoelectrons, coaxial helicity injection
- Can synergies be exploited to improve the start-up process?
- Scan NSTX, NSTX-U shot databases for correlations between pre-ionization parameters and start-up characteristics

Possible application to tokamak start-up
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Large access and view will let insert movable island divertor and image wetted area. Its scaling will be explored at low $B_p$ and low $i$.

1: Test/optimize different island divertors, move them relative to plasma and diagnose by Langmuir probes and IR imaging.
- Heating power being increased $\rightarrow$ increased heat load on divertor, easier to diagnose.
- Long pulses (several seconds or minutes).

2: Confirm and characterize more benign wetted area scaling in stellarators.
- Wetted area scales unfavorably (too narrow) with large $B_p$ in tokamaks [T. Eich, *PRL* 2011].
- Expected to broaden in low-shear stellarators thanks to low $i$ inside island [T. Pedersen].
Proto-CIRCUS
Small stellarators such as CIRCUS and TARALLO can test new confinement concepts and non-fusion applications

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CNT concept can be generalized to more than 2 tilted interlinked circular coils.

2 (CNT)  3  6  9

1 (LDX)  

D. Spong (ORNL)
Low Aspect Ratio Stellarators.
Coils just tilted or also inter-linked?

- Moroz, PPCF 1996
- Todd, PPCF 1990
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18 coil generalization of CNT would be more axisymmetric than 18 coil tokamak

- Tokamak, 18 TF coils.

- Tokamak-stellarator hybrid needing less $I_p$ than tokamak, for same rotational transform $\rightarrow$ less violent disruptions (similar to CTH).

- Variants:
  - Two sets of coils (not shown) tilted opposite to each other, to convert Tokamak in Stellarator before it disrupts?
  - Add VF interlinked coil on HFS?
Tilted coils need less current to achieve same transform. Also, have lower effective ripple than equivalent tokamak.
Analytic calculation of $B$ from circular coils makes field-line calculations very fast

$$B_r = \frac{Ca^2 \cos \theta}{\alpha^2 \beta} E(k^2)$$

$$B_\theta = \frac{C}{2\alpha^2 \beta \sin \theta} \left[ (r^2 + a^2 \cos 2\theta) E(k^2) - \alpha^2 K(k^2) \right]$$

$$\alpha^2 \equiv a^2 + r^2 - 2ar \sin \theta, \quad \beta^2 \equiv a^2 + r^2 + 2ar \sin \theta, \quad k^2 \equiv 1 - \alpha^2 / \beta^2$$

$$C \equiv \mu_0 l / \pi .$$

- 6 coils (old): ~13 minutes
- 6 coils (new): 11 seconds
- 6 single-filament coils: 0.6 seconds

Simpson et al, NASA 2001
Old numerical and new semi-analytical calculations agree on finite plasma ratio regions

- Effectively identical fieldlines traces between old and new m grids
- Calculated volumes consistent up to at least 5 significant figures

\( \text{VF/TF} = 1.5 \quad \text{QF/TF} = -0.5 \)
Poincare plot of a large volume plasma exhibits field period symmetry and good closed surfaces

- 6-coil configuration with VF/TF = 1.5 and QF/TF = -0.5
- Plasma volume = 2.05 L
Volume Calculations for 9 Coils

- Appearance of “edges” in contour for 9 coils that was not clearly visible for 6 coils
- Lower plasma volumes than 6 coils

<table>
<thead>
<tr>
<th>VF/TF</th>
<th>QF/TF</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.995</td>
<td>-9.2</td>
<td>1.35 L</td>
</tr>
<tr>
<td>1.930</td>
<td>-16.45</td>
<td>0.98 L</td>
</tr>
<tr>
<td>1.925</td>
<td>-16.45</td>
<td>0.24 L</td>
</tr>
</tbody>
</table>
Poincare Plot of a 9-Coil Plasma

- 9-coil configuration with VF/TF = 1.995 and QF/TF = -9.2
- Plasma volume = 1.35 L
Volume Calculations for 12 Coils

- Lower plasma volumes than 9 coils
- Same triangular-shaped regions as 6 and 9 coils

\[ VF/TF = 2.81 \]
\[ QF/TF = -21.5 \]
Poincare Plot of a 12-Coil Plasma

- 12-coil configuration with VF/TF = 2.81 and QF/TF = -21.5
- Plasma volume = 0.94 L
Progression to Higher Numbers of Coils

6-coil config; VF 0.5:2.5 x0.05; QF -15:15 x0.5

9-coil config; VF 1.4:2.2 x0.005; QF -30:0 x0.05

12-coil config; VF 2.6:3.0 x0.005; QF -40:10 x0.05

15-coil config; VF 3.5:3.7 x0.001; QF -50:20 x0.05
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Earlier Poincaré plots suggested need for $I_p = 2.5 \text{kA}$
Scan of coil currents, tilts and positions (under way) indicates $I_p$ can be as low as 0.8 kA (and lower?)

- Generator or amplifier of rotational transform?
- Tokamak-torsatron hybrid or pure torsatron? (or pure stellarator?)
- CNT doesn’t need $I_p \neq 0$
Tilts and radial locations of coils can be varied

TF supports, adjustable tilt=34-61° w.r.t. horizontal
Tilted interlinked TF coils being installed

6 interlinked TF coil rims

TF coil rim with axle

Generate 0.0875 T on axis for 2.45 GHz startup, ECH and ECCD
Construction of CIRCUS Tokamak-Stellarator was completed.

Tilted interlinked coils mounted on central column.
Acrylic vessel

Advantages
• High compressive strength
• Transparent to microwaves → easy heating & C
• Transparent to visible light → broad camera view

Disadvantages
High desorption rate

Nonetheless, $P=2.2\times10^{-5}$ torr, sufficient for EC startup.
Construction of CIRCUS Tokamak-Stellarator was completed.

- Installed 1kW, 2.45 GHz magnetron.
- Installing two paraboloidal mirrors, of which one steerable.
- Coils tested.
- Vacuum tested (2\cdot10^{-5} \text{ Torr}).
e-beam from filament biased at -100 V in gas at $10^{-5}$-$10^{-4}$ torr follows rotationally transformed field line
Bird’s-eye view
Electron gun can be scanned in 3D, for fine scans of flux surfaces in field-line mapping

Sliding feedthrough mounted on tiltable bellow
New vessel will allow better vacuum.
Coils will be external, cooled. Longer pulses.

Sections of new vacuum vessel:
glass cylinders in PTFE wedges.
Future work on CIRCUS

Experiments with present setup:

• Scan coil currents, with help of newly installed IGBTs, using numerical predictions as guidance.
• Scan e-gun in 3D (1 linear, 2 angular).
• Confirm rotational transform for e-beam initialized on high-field-side.
• Measure flux surfaces for various radial positions and tilts of coils. Identify parameter space where $I_p=0$. Compare with numerical predictions.

Improved setup:

• Microwave plasma in new vacuum vessel
• Larger plasmas will require $I_p \neq 0$. If ECCD not sufficient,
  – Central solenoid, for $I_p$ generation and Ohmic heating
  – New form of Rotating Magnetic Field CD (RMFCD)
  – Plasma Gunn [as in Proto-CLEO]
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TARALLO
Electron Cyclotron Resonance Ion Sources generate high-charge ions for accelerators

- Hot electrons (10keV), cold ions (eV)
- Trend to higher $f_{ECRH}$, improved confinement, reduced electron tails
- State of the art: 28GHz (1T at center, 3T at mirrors). Plans for 50GHz
- Open questions: stochastic heating, two-frequency phenomena

D-T Fusion Ignition!

III Gen.

Conventional ECRIS

SERSE

Plasmas and waveguides

Solenoids

Hexapole

Gas injection

Plasma chamb
Toroidal ECRIS will improve confinement and make better use of the field

- Bumpy torus + tor. hexapole
- $l=3$ classical stellarator
- TF “Mono-coil” inspired by MST
A toroidal ECRIS will make better use of B, allow higher $f_{\text{ECRH}}$, $n_e$ and confinement and ionization

- **Toroidal Apparatus for Resonant Absorption of Low Frequency Waves and Generation of highly charged Ions (TARALLO)**
- \( l=3 \) Stellarator
- Ion extraction
  - Loss cone
  - Divertor
  - Charge-dependent drifts
  - Pulsed saddle coil
  - Collector at dist.<FLR from plasma boundary
  - e.s.
  - Deflecting magnets
  - Techniques used in accelerators to pass particles from one storage ring or accelerator to the next, of higher energy (ECRIS would be first ring)

\[ R=35\text{cm} \]
\[ a=75\text{cm} \]
\[ B=2.5\text{T}, f=70\text{GHz} \]
Water-cooled copper, \( t\approx2\text{s} \)

Collaboration INFN Italy
COMSOL is being used to model fields, particle drifts and trajectories in TARALLO

Magnetic extraction of Bi$^+$ from outer midplane

Other ions, charge-states and initial conditions also modeled, to study selectivity in mass, charge and velocity space.
Magnetic configurations considered

Mono-coil TF uniformity

Rotated hexapole

Various $l$ and $n$ considered

Top view for $I_{\text{hex}}=30 \text{ kA}$ and $300 \text{ kA}$
Helical hexapole bends otherwise vertically drifting particles. Strong fields make boundary 3D.

Use drifts and non-axisymmetries to concentrate ion losses in specific $\theta$ and/or $\phi$, thus facilitating extraction.
Two ion extraction methods numerically demonstrated: 1) ExB

Dielectric used to simulate Debye shielding of capacitor’s fringing field
Two ion extraction methods numerically demonstrated: 2) magnetic deflector/divertor

Inboard extraction seems more efficient. Due to “meniscus”?
Summary and Conclusions

Columbia operates two stellarators and is designing a third one for a variety of studies:

1. **Columbia Non-neutral Torus (CNT)** – *with Ken Hammond et al.*
   - Present: Neutral plasmas, EC-heated. Langmuir probes profiles
   - Next: Heating and diagnostic upgrades.

2. **CIRCUS Tokamak-Torsatron hybrid** – *with Tony Clark, Michel Doumet et al.*
   - Present: Finished construction. Calculated Poincarè plots.
   - Next: First plasma. Experimental Poincarè plots.

3. **TARALLO Toroidal Electron Cyclotron Resonance Ion Source for Accelerators** – *with Claudia Caliri et al.*
   - Present: Single particle tracings endorse feasibility of various ion extraction techniques
   - Next: Confirm by modeling multiple interacting particles. Build device.
PF coil displacements inferred from photo-grammetry were unable to fully explain field errors.
Different coil displacements have different impact on rotational transform

(a)

(b)
$X$ vector consists of discrete parameters characterizing Poincaré cross section

\begin{align*}
R(\rho, \theta) &= R_0(\rho) + \sum_{m=1}^{M} R_{cm}(\rho) \cos(m\theta) + \sum_{m=1}^{M} R_{sm}(\rho) \sin(m\theta) \\
Z(\rho, \theta) &= Z_0(\rho) + \sum_{m=1}^{M} Z_{cm}(\rho) \cos(m\theta) + \sum_{m=1}^{M} Z_{sm}(\rho) \sin(m\theta) \\
R_{c1}(\rho) &= R_{c10} P_0(\rho) + R_{c11} P_1(\rho) + \ldots + R_{c1S} P_S(\rho) + \ldots
\end{align*}

- Begin by fitting a loop to each flux surface
- Parametrize loops using unique definitions for $\rho$ and $\theta$
First verification allowed only two degrees of freedom

- $X^*$ calculated for $-0.45^\circ$ change in tilt angle
- Correct solution obtained in 4 steps
Coil displacement parameters

\[ p = \{ x_{IL1}, y_{IL1}, z_{IL1}, a_{IL1}, b_{IL1}, x_{IL2}, y_{IL2}, z_{IL2}, a_{IL2}, b_{IL2} \} \]
Verification with 10 free coil parameters

Target: $z_{IL1} = 5 \text{ mm}$

Target: $b_{IL1} = 0.002; b_{IL2} = 0.004$
Error field diagnosis: future work

Improve precision of calculations
- Smaller finite differencing interval
- Generate $X^*$ using data from multiple current ratios

Allow for more sources of field error
- Deformations to the coils
- Uncompensated electrical leads

Evaluate scope of algorithm’s applicability
- When does it work or fail?
- Can it be applied to other devices?
Modulated heating and Langmuir probe measurements suggest plasma decaying in 2.3 ms
Tunable 1-3 MHz, 4 MW, 10 ms source could dramatically heat ions & electrons for several $\tau_E$

- Pulse-modulating triodes
- Formerly from UW Levitated Octupole and HBT-EP

- Ion Cyclotron
- Lower Hybrid
- Sub-harmonic sub-thermal Alfven Wave heating and CD
IGBTs will allow fine adjustment of coil currents and scan of possible plasma equilibria

- Two banks of IGBTs in series with VF and QF coils control coil-currents via voltage across the gates of the IGBTs
- IGBTs because of high maximum collector currents and high power dissipation ratings
- IGBTs installed
- Their LabView control under installation