In the Volpe group we...
...magnetically steer disruptive instabilities and suppress them by wave-driven currents, ...
...design and build metamaterials of new optical properties (e.g., reverse chromatic aberration), ...
...model and invent new ways of probing the plasma (e.g., its magnetic field) by means of e.m. waves.
Stellarators: the honey-dipper stable approach to fusion

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What are stellarators?

Beautiful helical cages that confine the plasma without asking the madman to confine itself.

Field-lines are helical because of:

- Nested surfaces (← topology)
- Equilibrium (← force balance)
- Stability (← honey dipper)
- Drift compensation (← ~Möbius strip)
Why not fusion at LHC?

Fusion requires:

✓ reactants to collide at high energy (or $T$)

✗ many reactants:
  – Large volumes and/or high density $n$

✗ “thermal insulation” (confinement) of input and fusion energy, and of reactants $\rightarrow$ more reactions
  – Large distances (MCF)
Let’s have an orderly (confined) – disorderly (thermonuclear) approach

No confinement (0D).

(ionized) gas can expand in 3D.

Constrain on straight field-lines (1D).
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Remove end losses.
Constrain on closed lines.
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Remove end losses.
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**Twist** field-lines.
Constrain on closed nested surfaces (2D).
Losses are 1D (minor radius).
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Slow them down by a potential well, e.g. multi-cusp →
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Classical stellarator

Möbius strip cheats drifts of *passing* particles...
Let’s have an orderly (confined) – disorderly (thermonuclear) approach

No confinement (0D). (ionized) gas can expand in 3D.

Constrain on straight field-lines (1D).

Remove end losses. Constrain on closed lines.

**Twist** field-lines. Constrain on closed nested surfaces (2D). Losses are 1D (minor radius).

Slow them down by a potential well, e.g. multi-cusp.

**Put it all together.**

Modular optimized stellarator

... but not of *trapped* particles.
Purely toroidal field cannot contrast $\nabla p$

- Force balance $j \times B = \nabla p$ requires $j \times B$ in $r$ direction

- Toroidal $B$ →
  → vertical $\mu_0 j = \nabla \times B$ →
  → $j \times B$ in $R$ direction

- Conclusion: $B$ cannot be purely toroidal → helical $B$
Helical field-lines carry plasma from unstable outside to stable inside of torus

Top view:

plasma = heavy fluid

$B = \text{“light fluid”}$

$g_{\text{eff}} = \frac{v^2}{R}$ centrifugal force

Similar to how twirling a honey dipper prevents honey from dripping.

Credit: F. Wagner, G. Hammett et al.
Recapitulating

Field-lines must be helical because of:

• Nested surfaces (← topology)
• Drift compensation (← ~ Möbius strip)
• Equilibrium (← force balance)
• Stability (← honey dipper)
Tokamaks and Stellarators are the two main approaches to generation of helical fields

- Inductive or non-inductive current in plasma
  - Ohmically heats the plasma
  - Generates a poloidal field

- Steady state
- No current-driven instabilities
- Resilient to pressure-driven instabilities

- Disadvantages: complexity & sub-mm precision
QUESTIONS

Do the coil need to be so complicated?
Is the stellarator still stable at very high pressure?

Can we combine tokamak’s and stellarator’s advantages?

Can we use stellarators in non-fusion basic research?
Columbia operates two stellarators and is designing a third one

Do the coil need to be so complicated?
Is the stellarator still stable at very high pressure?

1. Columbia Non-neutral Torus (CNT)  
   – with Ken Hammond et al.

Can we combine tokamak’s and stellarator’s advantages?

2. CIRCUS Tokamak-Torsatron hybrid  
   – with Tony Clark, Michel Doumet et al.

Can we use stellarators in non-fusion basic research?

3. TARALLO Toroidal Electron Cyclotron Resonance Ion Source for Accelerators  
   – with Claudia Caliri
CNT
CNT was built in 2002-2005 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>
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<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 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
CNT now confines neutral, microwave-heated plasmas for several minutes
1kW of ECH at 2.45 GHz is sufficient to obtain $T_e = 6-9$ eV

Langmuir probe measurements

$n_e \approx 10^{16} \text{m}^{-3} < 7 \times 10^{16} \text{m}^{-3}$ (underdense ECH)
Modulated heating and Langmuir probe measurements suggest plasma decaying in 2.3 ms.
Flat profile is consistent with broad injection and deposition

\[ \varphi = 0.083\pi = 15 \text{ deg} \]
New 10 kW, 2.45 GHz Magnetron being installed

Muegge GmbH
10 kW will be launched from different $\varphi$, more tokamak-like. Will require higher $B_T$ than usual.

Conformal launcher might enable first ever direct excitation of Electron Bernstein Waves (no Mode Conversion)
100 kW of EBW heating could lead to $\beta \approx 10\%$
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.
...and $\sim 10^{19}$ m$^{-3}$ densities, higher than at lower power (thanks to favorable radiative scaling)
$T_e$ of hundreds of eV by Electron Bernstein Waves, keV by Electron Cyclotron Heating

$P = 100$ kW

Electron temperature, eV

Electron temperature, eV

Magnetic field, T

$2.45$ GHz

$4.6$ GHz

$8.0$ GHz

$28.0$ GHz

inaccessible
Four 125 kW, 8 GHz klystrons can be borrowed from the Frascati Tokamak
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
Large CNT vessel will enable new studies

- Plasma far from wall → different interaction (MAST & NSTX)
- Easily insert, move or replace coils, mirrors, diagnostics etc. in the vessel:
  1. **Interaction with moving limiter/divertor**
     - EBWs
     - Island divertor
  2. **First Experimental Study of Sensitivity to Coil Misalignment**
     - Estimated/calculated tolerance 0.3mm at W7-AS, 1mm at LHD
     - Do we really need this tolerance? In every direction and for every coil?
     - Measure effects of misalignments on:
       - Equilibrium, stability, confinement, transport, ion losses, etc.
Large CNT vessel will enable new studies (cont’d)

Easily insert, move or replace coils, mirrors, diagnostics etc. in vessel:

3. **Plasma Response to Error Fields**
   - Small perturbing coil
   - 1D array of inductive and/or Hall probe (3 components)
   - Measure sensor response (in G/A) to d.c. and a.c. perturbations as function of position (of sensors and actuators) and frequency (of actuators)
     - Like tapping drum in various positions to infer global modes of vibration
     - Some modes “vibrate” more easily, some are even amplified by plasma response.
   - Experimental equivalent of SVD of “Transfer Matrix” from machine errors to plasma deformation [Boozer, PoP2011]
   - Generalize to other effects of EFs (on confinement, stability, transport, rotation etc.)

4. **Periscope or Endoscope to study 2.45GHz discharge cleaning**
Onion-peeling algorithm (~3D generalization of Abel inversion) allowed extracting emissivity profiles from visible images

Portion 1 of image (without coils or instruments in background)

1. Vacuum flux surfaces calculated by Runge-Kutta field-line tracer
2. Layer between two surfaces assumed to have uniform emissivity
3. Luminosity per unit length, \( L_j \), of j-th plasma layer contributes to brightness \( b_i \) of pixel \( i \) in proportion to its "width" \( w_{ij} \), as "seen" by that pixel. Hence, similar to matrix inversion,

\[
L_j = \frac{\sum_i b_i \left( \frac{w_{i,j}}{t_i} \right)^k}{\sum_i w_{i,j} \left( \frac{w_{i,j}}{t_i} \right)^k}
\]

where \( t_i = \) total length of chord \( i \). \( k = \) exponent to enhance/decrease \( w_{ij}/t_i \) weighting.
Emissivity peaks at edge as expected. Some discrepancies from distinct portions of same plasma.
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
CNT concept can be generalized to more than 2 tilted interlinked circular coils.

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

- Moroz, PPCF 1996
- Todd, PPCF 1990
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.
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.
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 \cdot 10^{-5} \text{ Torr}).
Flux surface mapping will experimentally test rotational transform by tilted coils

Experimental plan:
• Measure flux surfaces for various radial positions and tilts of coils, and compare with calculations. Introduce deliberate error fields.
• Optimize configuration for minimum $I_p$ requirement. $I_p > 0.8$ kA needed? Numerical study under way.
• Fast-camera studies of plasma formation by EC start-up.

Future improvements:
• Water cooling of coils, for longer shots or higher repetition rate
• 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]
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.

SERSE

Conventional ECRIS

$T_{\text{ont}}$ (eV)

$n_e \tau_e$ (cm$^{-3}$sec)
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 $f_{ECRH}$, $n_e$, 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.
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.
Research opportunities for Undergrads!

CNT group

CIRCUS and TARALLO groups
Back-up Slides
Observed $T_e$ are consistent with injected power, confinement stellarator scaling and cutoff $n_e$

$$\tau_{ISS95} = 0.256 R^{0.65} a^{2.21} B^{0.83} n_e^{0.51} P^{-0.59} l^{0.4}$$
Helicon Heating is also considered

- high $n_e = 10^{19} - 10^{20}$ m$^{-3}$ target for EBWs
- CNT test-bed for new fusion diagnostics (when low $B$ OK)
- Fairly new in Stellarators and Fusion, except for HELIAC and EAST (He)
- Frequencies $\omega_{ci} < \omega < \omega_{ce} < \omega_{pe}$
- Heavier species (Ar?) $\rightarrow$ lower $\omega_{ci}$, better frequency separation
- Some fast e-. Low CD efficiency ($\sim T_e/n_e$). Heating.
- Landau- and collisionally damped on electrons
- Alternative to ICRH, traditionally difficult in stellarators?
- Can be used for startup [Chen]
CNT is:

1. a small stellarator capable of physics research relevant to big stellarators
   - Error Fields
   - Divertor physics
   - High \( \beta \) MHD
   - Trapped particles physics

2. a technological test-bed
   - Copper coils inertially cooled by LN2 (FIRE, QUASAR) or cold gas (FAST)

3. a plasma on which to test novel diagnostics:
   - Microwaves
     - Metamaterial Lenses of Reverse Chromatic Aberration
     - Mode-Conversion Oblique Reflectometry Imaging to measure edge q-profile and magnetic structures
     - +5 unpublished ideas
3. a plasma on which to test novel diagnostics (cont’d):
   – Various ideas on Magnetics
   – Various ideas on Optics

4. a curiosity-driven experimental exploration of basic wave physics
   – EBWs
     • Direct excitation
     • Mechanisms degrading XB conversion at UHR
   – Helicon
   – Finite wavelength and/or finite Larmor radius effects (both are large)
   – Comparison with full-wave modeling
     • complicated plasma shape demands numerical modeling; ray tracing not applicable; full-wave applicable and, in fact, relatively easy
Heating 1: ECH and EBWH

- 2.45GHz magnetron, air-cooled, 1kW, outside vessel, no focusing
- Next: 2.45GHz magnetron, water-cooled, 10kW, outside vessel, focusing and directionality
- After next: 100kW class (8 GHz?)

- For comparison, 6kW at TJ-K and 26kW at WEGA

- In addition to EC Heating, also:
  - EC Startup
  - Collisional Heating at UHR
  - Transport studies, by power modulation (heat waves)
  - Direct coupling of EBWs, thanks to low $f$ and low edge $T_e$