

magwell-test

July 23, 2022

1 Synopsis

Update 3: I think this implementation is correct. Can't find anything that would be wrong. Maybe send me an ATF STELLOPT run though, (I only have access to educational VMEC). If we want the plots to always look alike between STELLOPT and DESC, I don't know how to achieve that in the code I've written. I think any differences are due to more fundamental differences in the STELLOPT and DESC code.

- New grid update fixed the symmetry bug I mentioned in June.
- Heliotron is a perfect match to STELLOPT with symmetry off, very close with symmetry on.
- All implementations of the Magnetic Well parameter between DESC and STELLOPT agree on crossing. Educational VMEC disagrees with STELLOPT on Heliotron crossing and has a weird curve for ATF. I don't really trust educational VMEC's plots because of this. (I read through edu-vmec's GitHub history, and it looks like their master branch has fixes that are not in the educational branch I'm using. Their master branch is missing files to compile locally, so I can't use that).
- Increasing the number of surfaces (rho resolution) on educational VMEC input from 256 to 1024 didn't change anything significantly. Educational VMEC's heliotron plot's crossing did shift left toward the point where the STELLOPT data and DESC magnetic wells cross.

Update 2: works with arbitrary grids and computes magnetic well parameter over multiple flux surfaces simultaneously Made use of the `surface_integrals` functionality I added while coding the new rotational transform function. The objective will still function in the same way as before if a single rho surface is given as input. However, computing magnetic well over multiple flux surfaces at once offers at least two benefits. It * Simplifies end user code. They don't have to create routines and loop through things. * Increases performance. I used to wait for this jupyter notebook to run for 30 minutes to get values to plot. Now it runs in 1 minute. * Please see [a bug in the grid class](#). The solution to this bug for grids with a single rho surface is simple. If the functions I added to `compute.utils` are used then the developer/user doesn't have to worry about it. However, for multiple rho surface grids, the fix isn't as simple. Until that fix is implemented, if the user wants magnetic well computed on a grid with multiple values of rho, for best accuracy they need to set NFP=1 in the grid provided to magnetic well.

Update 1: alternative version of magnetic well in Landerman paper added. It seems to have more responsive curves, and it has the same abrupt change as STELLOPT for HELIOTRON. It yields a perfect match for Heliotron.

1.1 the Bad

The curves produced by DESC and STELLOPT for the magnetic well parameter as a function of ρ look different. I think STELLOPT does not implement the well parameter we thought it does. We should just pay attention to the crossing.

1.2 the Good

The magnetic well parameter computed by DESC matches the sign of the magnetic well parameter computed by STELLOPT. This is technically all we need.

The volume computation is now 100% correct. The solution to the bug in the `grid.py` class works, which was necessary to correct volume and $dv/d\rho$. An [explanation to the solution is given here](#). Might be useful in case we have run into this bug somewhere else in the code.

All the [plots](#) of DESC's intermediate quantities are consistent with each other. For every point below, I have confirmed their validity with code tests and math where applicable. We should be sure to preserve these signs if any modifications are made:

- The volume of the torus is exactly quadratic with ρ . The derivative of the volume enclosed by the flux surface is exactly linear. For the other stellarators, the volume and derivative are approximately quadratic and linear, respectively. The derivative computations also flatten when the volume curves linearize, and the opposite holds as well. All this matches our expectation that volume $\sim \rho^2$.
- The volume enclosed by the $\rho=1$ surface matches the volume of the stellarator as computed by `data["V"]` on a grid with a sequence of ρ values.
- The derivative of the thermal pressure average is always negative. This is good since our notion that the well parameter being positive implies stability is only valid when thermal pressure decreases away from the magnetic axis ($\rho=0$). Otherwise negative well parameters would imply stability.
- The derivative of the thermal pressure average looks very similar for stellarators with similar pressure profile inputs.
- Confidence in the new more complicated flux surface average
 - We now properly differentiate under the flux surface average operation. Pushing a volume derivative into a flux surface average requires more care than simply differentiating under the integral. We want to do this in the first place to take advantage of automatic differentiation of `B_r` and `p_r`.
 - Have shown the implementation has the desired additive homomorphism property; meaning $\text{average}(a + b) = \text{average}(a) + \text{average}(b)$. Sanity check for correctness.
 - Confirmed `jnp.mean(f) / jnp.mean(sqrt(g))` always $= \text{jnp.sum(dtdz * f)} / dv/d\rho$. Helps confirm $dv/d\rho$ is correct among other things.
 - Proved that this new flux surface average is an identity operation for the average of any quantity constant over the surface.
- The thermal pressure is a flux surface function; it is constant on a surface of constant rho. Therefore, the average of thermal pressure over a flux surface should be an identity operation. This is reflected in the code. Also, we take advantage of the homomorphism discussed above to avoid an unnecessary flux surface average operation.
- The derivative of the magnetic pressure average is positive (negative) precisely when B_2 average is increasing (decreasing). We should expect this since magnetic pressure $\sim B_2$, and its average over a surface should likely share that relation.

- No jacobian sign errors. FYI: we always want them to be positive here.
- The volume derivative is not necessary for the magnetic well parameter from Greene's paper. I replaced the flux surface label of volume with ρ in the magnetic well formulas derived in the Greene's paper. The output of the magnetic well plot (this version is in purple color) is the same (as the volume derivative version in blue), ignoring the scale. Plots of both are included.

1.3 the Pretty

This notebook should make it easy to inspect intermediate variables in the `MagneticWell` class as well as compute quantities for all the stellarators in a concise manner. Add an entry to the dictionary and everything is automatic. Note this notebook should run pretty quickly. If the plots for many stellarators at once are requested, increase the memory given to jupyter notebook and/or compute on 3 stellarators at a time instead of 5+, and/or reduce plot dpi.

~~Given this, if the equilibrium solutions DESC and STELLOPT are computing magnetic well parameters on are indeed the same, I think any issue must be in the automatic differentiation of B_r and p_r .~~

```
[1]: import sys
import os

sys.path.insert(0, os.path.abspath('.'))
sys.path.append(os.path.abspath('../'))
```



```
[2]: %matplotlib inline
import matplotlib.pyplot as plt
import numpy as np

from netCDF4 import Dataset
import pickle
import scipy.io as sio
import desc.io

from desc.compute import compute_geometry, data_index
from desc.equilibrium import Equilibrium
from desc.grid import LinearGrid
from desc.objectives import MagneticWell
from desc.plotting import plot_surfaces
from desc.transform import Transform
```

DESC version 0.5.1+100.gc4b3314.dirty, using JAX backend, jax version=0.2.25,
jaxlib version=0.1.76, dtype=float64
Using device: CPU, with 5.36 GB available memory

```
[3]: np.set_printoptions(precision=4, floatmode="fixed")
```

```
[4]: class MagneticWellVisual:
    """
    To print and plot more (less) quantities, add (remove) them to the dict
    returned from MagneticWell.compute().
    Everything else is automatic.
    """

    def __init__(
        self,
        name,
        eq=None,
        use_pickle=True,
        rho=np.linspace(1 / 64, 1, 64),
    ):
        """
        Make a MagneticWellVisual from either the provided equilibrium
        or the final equilibrium loaded from the output.h5 solution.

    Parameters
    -----
    name : str
        Name of the equilibrium.
    eq : Equilibrium
        The equilibrium.
    use_pickle : bool
        True to use compute values from a previous run stored in pickle
        file; False to recompute.
    rho : ndarray
        The flux surface values to compute the magnetic well on.
        """
        self.name = name
        if eq is None:
            eq = desc.io.load(load_from="../examples/DESC/" + name + "_output.
        h5")[-1]
            self.eq = eq

        if use_pickle:
            with open(name + " DESC magwell.pkl", "rb") as file:
                self.st = pickle.load(file)
            self.rho = self.st["volume"][0]
            self.has_values = True
        else:
            # values are tuples of (x[i], y[i]) of plotable data
            # y points are cached when compute_plot() is called
            self.st = dict()
            try:
                mat = sio.loadmat(name + "_magwell.mat")

```

```

        self.st["0. STELLOPT Magnetic Well"] = mat["rho"],_
        ↵mat["magwell"]
            rho = mat["rho"]
        except FileNotFoundError:
            pass

    try:
        f = Dataset("../iota/edu-vmec/input-iota/wout_" + name + ".nc")
        # print(f.variables.keys())
        vmec_rho = np.sqrt(
            f.variables["phi"] / np.array(f.variables["phi"])[-1]
        )
        vmec_well = np.asarray(f.variables["DWell"])
        self.st["0. VMEC Magnetic Well"] = vmec_rho, vmec_well
    except FileNotFoundError:
        pass

    self.rho = rho
    self.has_values = False

def print_values(self, grid=None):
    """
    Parameters
    -----
    grid : LinearGrid
        The grid used for a MagneticWell objective.
        The default grid=None uses the rho=1 flux surface.
    """
    print(self.name)
    print(self.eq)
    mw = MagneticWell(eq=self.eq, grid=grid)
    print("grid.spacing(dr,dt,dz)", mw.grid.spacing[0])
    m = mw.compute(
        self.eq.R_lmn,
        self.eq.Z_lmn,
        self.eq.L_lmn,
        self.eq.p_l,
        self.eq.i_l,
        self.eq.c_l,
        self.eq.Psi,
    )
    for key, val in sorted(m.items()):
        print(key, val)
    self._print_data_V()
    print()

def _print_data_V(self):

```

```

"""
Print the volume of the stellarator device as computed by data["V"].
Should match V surface integral when the default grid with rho = 1
is used to construct the MagneticWell() object.
"""

grid = LinearGrid(
    L=self.eq.L_grid,
    M=self.eq.M_grid,
    N=self.eq.N_grid,
    NFP=self.eq.NFP,
    sym=self.eq.sym,
)
R_transform = Transform(
    grid, self.eq.R_basis, derivs=data_index["sqrt(g)"]["R_derivs"], ↴
build=True
)
Z_transform = Transform(
    grid, self.eq.Z_basis, derivs=data_index["sqrt(g)"]["Z_derivs"], ↴
build=True
)
data = compute_geometry(self.eq.R_lmn, self.eq.Z_lmn, R_transform, ↴
Z_transform)
print('data["V"]', data["V"])

# same as other compute_plot but builds plot through computing on single ↴
rho surfaces
# def compute_plot(self):
#     """Compute and cache MagneticWell.compute() values."""
#     if self.has_values:
#         return
#
#     for i in range(len(self.rho)):
#         m = MagneticWell(
#             eq=self.eq,
#             grid=LinearGrid(
#                 M=self.eq.M_grid,
#                 N=self.eq.N_grid,
#                 NFP=self.eq.NFP,
#                 sym=self.eq.sym,
#                 rho=self.rho[i],
#             ),
#             ).compute(
#                 self.eq.R_lmn,
#                 self.eq.Z_lmn,
#                 self.eq.L_lmn,
#                 self.eq.p_l,
#                 self.eq.i_l,

```

```

#           self.eq.c_l,
#           self.eq.Psi,
#       )
#       for key, val in m.items():
#           self.st.setdefault(key, (self.rho, np.empty_like(self.
# ↪rho)))[1][i] = val
#       self.has_values = True

def compute_plot(self):
    """Compute and cache MagneticWell.compute() values."""
    if self.has_values:
        return

    m = MagneticWell(
        eq=self.eq,
        grid=LinearGrid(
            M=self.eq.M_grid,
            N=self.eq.N_grid,
            NFP=1, # required for accuracy when grid.num_rho != 1
            sym=self.eq.sym,
            rho=self.rho,
        ),
        ).compute(
            self.eq.R_lmn,
            self.eq.Z_lmn,
            self.eq.L_lmn,
            self.eq.p_l,
            self.eq.i_l,
            self.eq.c_l,
            self.eq.Psi,
        )
    for key, val in m.items():
        self.st[key] = self.rho, val
    self.has_values = True

def save(self):
    """Save computed values to pickle file."""
    with open(self.name + " DESC magwell.pkl", "wb") as file:
        pickle.dump(self.st, file)

@staticmethod
def _color(key):
    """Return the correct plot color."""
    if "O. STELLOPT" in key:
        return "tab:green"
    if "O. VMEC" in key:
        return "tab:brown"

```

```

if "1." in key:
    return "tab:orange"
if "2." in key:
    return "tab:purple"
return "tab:blue"

def plot(self, dpi=300):
    """Plot all quantities from compute_plot() in st."""
    fig, ax = plt.subplots(
        nrows=3,
        ncols=(len(self.st) + 2) // 3,
        figsize=(len(self.st) * 3, 15),
        dpi=dpi,
    )
    ax = ax.flatten()

    for i, e in enumerate(sorted(self.st.items())):
        key, val = e
        x, y = val

        # edu umec usually blows up near rho=1. messes up plot scaling if
        ↵ included
        if key == "0. VMEC Magnetic Well":
            x = x[:-3]
            y = y[:-3]

            color = MagneticWellVisual._color(key)
            ax[i].scatter(x, y, color=color, s=(5 if len(x) > 128 else 10))
            ax[i].plot(x, y, color=color)
            ax[i].set(xlabel=r"\rho", ylabel=key, title=self.name,□
            ↵ facecolor="white")
            if "Magnetic Well" in key:
                if np.any(~np.isclose(y, 0)):
                    ax[i].set(yscale="symlog" if np.any(y < 0) else "log")
                    ax[i].axhline(color="tab:red")
            ax[i].grid()

def plot_magnetic_wells(self, dpi=300):
    """Plots the magnetic wells together on the same scale."""
    fig, ax = plt.subplots(dpi=dpi)

    # computed on other codes
    if (key := "0. STELLOPT Magnetic Well") in self.st:
        color = MagneticWellVisual._color(key)
        rho, well = self.st[key]
        ax.plot(rho, well, color=color, label="STELLOPT")
        ax.scatter(rho, well, color=color, s=1)

```

```

if (key := "0. VMEC Magnetic Well") in self.st:
    color = MagneticWellVisual._color(key)
    rho, well = self.st[key]
    # edu vme usually blows up near rho=1. messes up plot scaling if ↴
    ↴ included
    rho, well = rho[:-3], well[:-3]
    ax.plot(rho, well, color=color, label="edu-vmec")
    ax.scatter(rho, well, color=color, s=1)

    # computed with DESC
    well = self.st["1. DESC Magnetic Well: M. Landreman eq. 4.19"][1]
    color = MagneticWellVisual._color("1.")
    ax.plot(
        self.rho,
        well,
        color=color,
        label="DESC M. Landreman eq. 4.19",
    )
    ax.scatter(self.rho, well, color=color, s=1)

    well = self.st["2. DESC Magnetic Well: M. Landreman eq. 3.2 with rho * ↴
    ↴ d/drho"][1]
    color = MagneticWellVisual._color("2.")
    ax.plot(
        self.rho,
        well,
        color=color,
        label="DESC M. Landreman eq. 3.2 with rho * d/drho",
    )
    ax.scatter(self.rho, well, color=color, s=1)

    well = self.st["3. DESC Magnetic Well: M. Landreman eq. 3.2"][1]
    color = MagneticWellVisual._color("3.")
    ax.plot(self.rho, well, color=color, label="DESC M. Landreman eq. 3.2")
    ax.scatter(self.rho, well, color=color, s=1)

    ax.set(
        ylim=[-0.25, 0.25],
        xlabel=r"\rho",
        ylabel="magnetic well",
        title=self.name + " well zoomed",
        facecolor="white",
    )
    ax.axhline(color="tab:red")
    ax.grid()

```

```

    fig.legend(fontsize="xx-small")
    fig.savefig(self.name + " magnetic wells sym default.png")

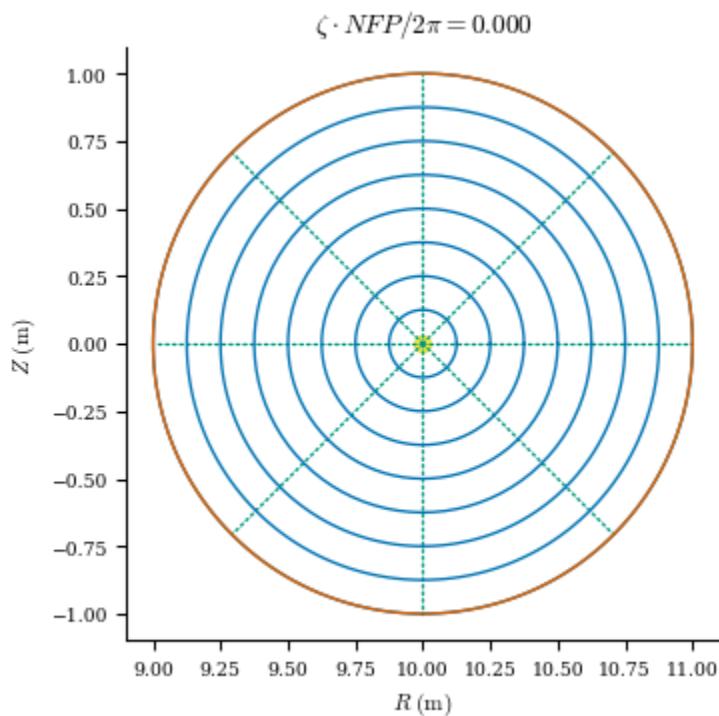
```

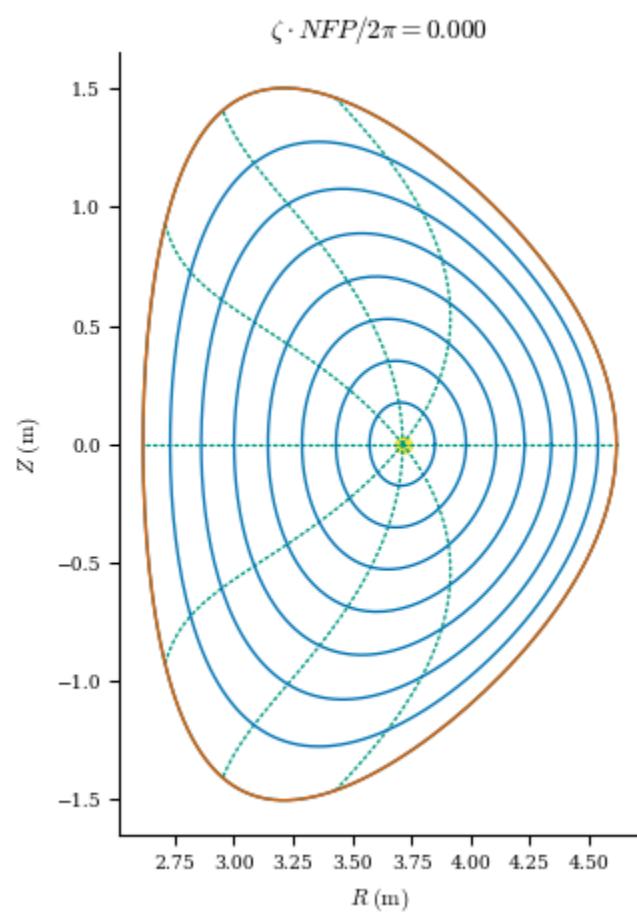
```
[5]: torus = MagneticWellVisual("torus", Equilibrium())
dshape = MagneticWellVisual("DSHAPE")
heliotron = MagneticWellVisual("HELIOTRON")
atf = MagneticWellVisual("ATF")
axisym = MagneticWellVisual("AXISYM")
stellarators = (torus, dshape, heliotron, atf, axisym)
```

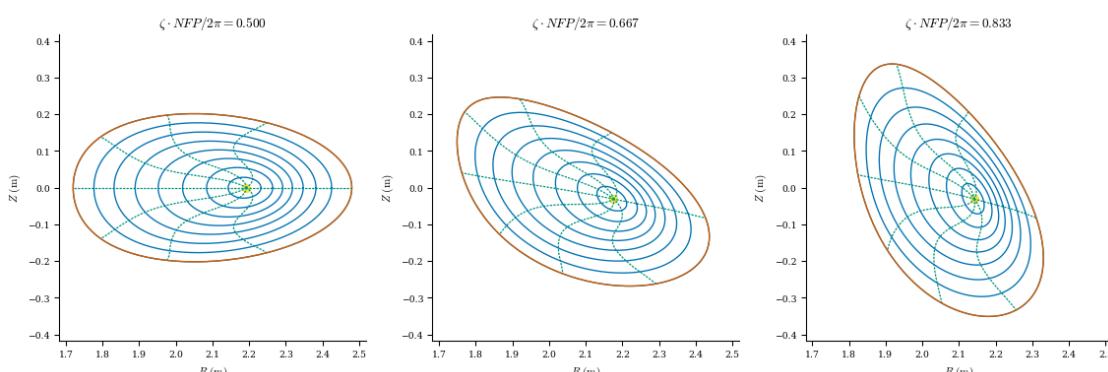
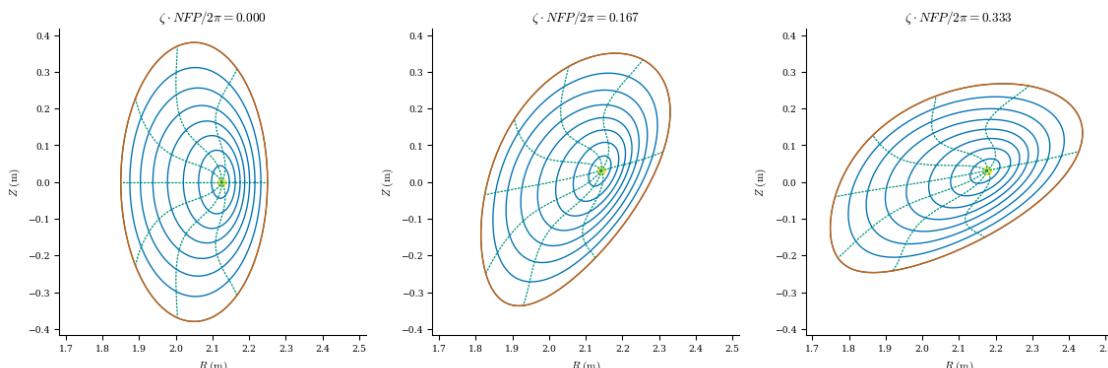
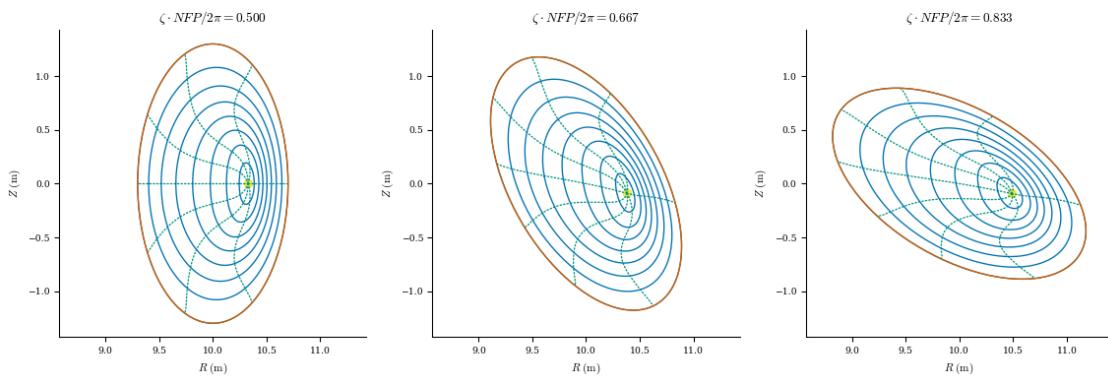
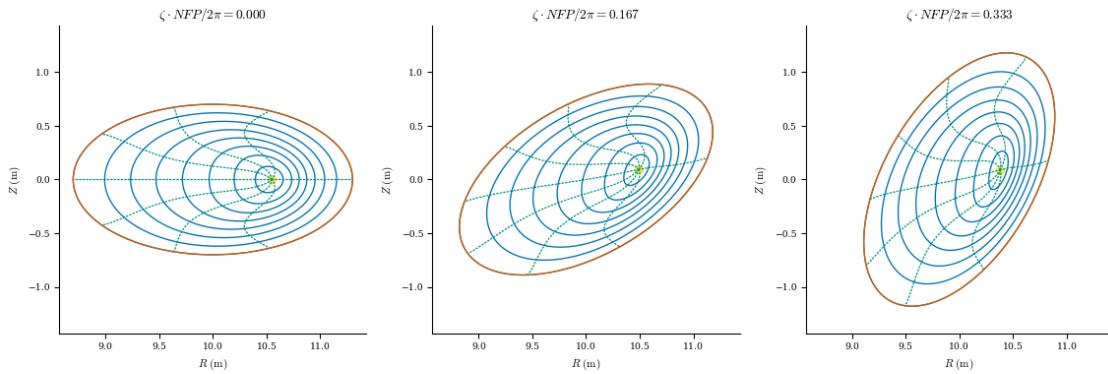
```
/home/kaya/Documents/edu/pton/plasma/DESC/desc/configuration.py:344:
UserWarning: Must specify either iota or current. Using default profile of
iota=0.
    warnings.warn(
/home/kaya/Documents/edu/pton/plasma/DESC/desc/io/hdf5_io.py:108:
RuntimeWarning: Save attribute '_current' was not loaded.
    warnings.warn(
```

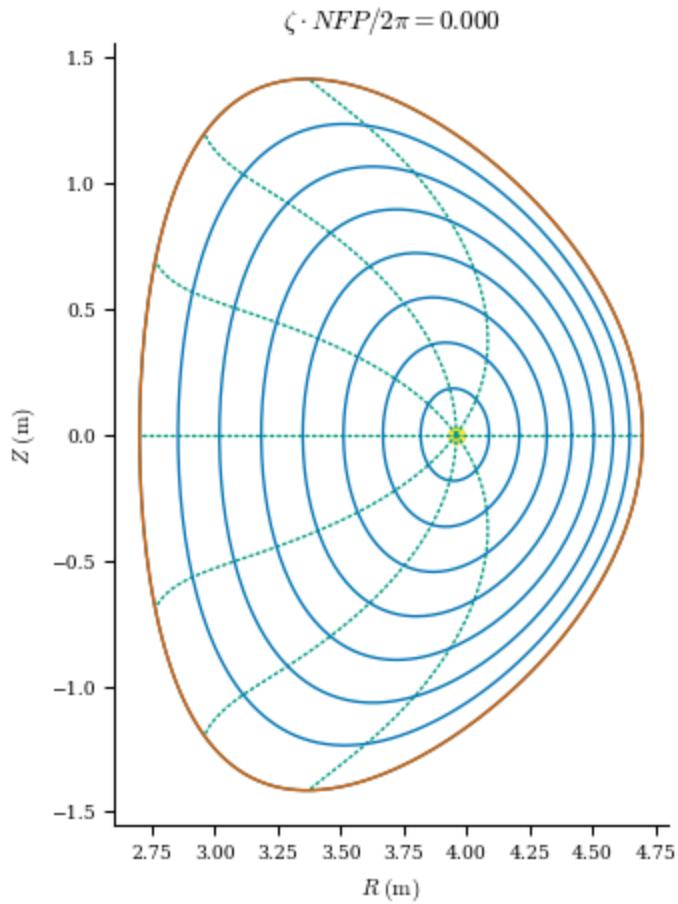
2 Equilibrium plots

```
[6]: # to make sure equilibrium were solved correctly on my computer
for s in stellarators:
    plot_surfaces(s.eq)
```









3 $\rho = 1$ flux surface

```
[7]: for s in stellarators:
    s.print_values()
```

torus
Equilibrium at 0x7f46d93d7700 (L=1, M=1, N=0, NFP=1, sym=False,
spectral_indexing=ansi)
Precomputing transforms
grid.spacing(dr,dt,dz) [1.0000 1.2566 6.2832]
1. DESC Magnetic Well: M. Landreman eq. 4.19 [0.0000]
2. DESC Magnetic Well: M. Landreman eq. 3.2 with rho * d/drho [-3.2159e-16]
3. DESC Magnetic Well: M. Landreman eq. 3.2 [-1.6080e-16]
B square average [0.1013]
d(magnetic pressure average)/drho [-3.2584e-17]

```

d(thermal pressure)/drho [0.0000]
d(total pressure average)/drho [-3.2584e-17]
d(total pressure average)/dvolume [-8.2537e-20]
d^2(volume)/d(rho)^2 [394.7842]
dtdz [39.4784]
dvolume/drho [394.7842]
volume [197.3921]
data["V"] 197.39208802178715

DSHAPE
Equilibrium at 0x7f46d92fdb30 (L=26, M=13, N=0, NFP=1.0, sym=1,
spectral_indexing=fringe)
Precomputing transforms
grid.spacing(dr,dt,dz) [1.2599 0.1466 7.9163]
1. DESC Magnetic Well: M. Landreman eq. 4.19 [0.0000]
2. DESC Magnetic Well: M. Landreman eq. 3.2 with rho * d/drho [0.0629]
3. DESC Magnetic Well: M. Landreman eq. 3.2 [0.0369]
B square average [0.0575]
d(magnetic pressure average)/drho [0.0036]
d(thermal pressure)/drho [0.0000]
d(total pressure average)/drho [0.0036]
d(total pressure average)/dvolume [2.1337e-05]
d^2(volume)/d(rho)^2 [305.9274]
dtdz [39.4784]
dvolume/drho [169.7811]
volume [99.4570]
data["V"] 99.1767790025823

HELIOTRON
Equilibrium at 0x7f46d8fc2760 (L=24, M=12, N=3, NFP=19.0, sym=1,
spectral_indexing=fringe)
Precomputing transforms
grid.spacing(dr,dt,dz) [3.3620 0.5559 0.0855]
1. DESC Magnetic Well: M. Landreman eq. 4.19 [0.0000]
2. DESC Magnetic Well: M. Landreman eq. 3.2 with rho * d/drho [-2.2638]
3. DESC Magnetic Well: M. Landreman eq. 3.2 [-0.9240]
B square average [0.1253]
d(magnetic pressure average)/drho [-0.2837]
d(thermal pressure)/drho [0.0000]
d(total pressure average)/drho [-0.2837]
d(total pressure average)/dvolume [-0.0006]
d^2(volume)/d(rho)^2 [1483.7368]
dtdz [39.4784]
dvolume/drho [440.0806]
volume [179.6268]
data["V"] 180.78725668914205

```

ATF

```

Equilibrium at 0x7f46d8f25b80 (L=24, M=12, N=4, NFP=12.0, sym=1,
spectral_indexing=fringe)
Precomputing transforms
grid.spacing(dr,dt,dz) [2.8845 0.5331 0.1162]
1. DESC Magnetic Well: M. Landreman eq. 4.19 [0.0000]
2. DESC Magnetic Well: M. Landreman eq. 3.2 with rho * d/drho [-1.3759]
3. DESC Magnetic Well: M. Landreman eq. 3.2 [-0.5825]
B square average [16.7004]
d(magnetic pressure average)/drho [-22.9789]
d(thermal pressure)/drho [0.0000]
d(total pressure average)/drho [-22.9789]
d(total pressure average)/dvolume [-3.1056]
d^2(volume)/d(rho)^2 [18.0245]
dtdz [39.4784]
dvolume/drho [7.3991]
volume [3.1325]
data["V"] 3.1505967937703065

```

AXISYM

```

Equilibrium at 0x7f46d93d7d00 (L=40, M=20, N=0, NFP=1.0, sym=1,
spectral_indexing=fringe)
Precomputing transforms
grid.spacing(dr,dt,dz) [1.2599 0.0965 7.9163]
1. DESC Magnetic Well: M. Landreman eq. 4.19 [0.0000]
2. DESC Magnetic Well: M. Landreman eq. 3.2 with rho * d/drho [-0.1511]
3. DESC Magnetic Well: M. Landreman eq. 3.2 [-0.0958]
B square average [0.0683]
d(magnetic pressure average)/drho [-0.0103]
d(thermal pressure)/drho [0.0000]
d(total pressure average)/drho [-0.0103]
d(total pressure average)/dvolume [-6.6500e-05]
d^2(volume)/d(rho)^2 [493.9344]
dtdz [39.4784]
dvolume/drho [155.3259]
volume [98.4592]
data["V"] 98.19957214489737

```

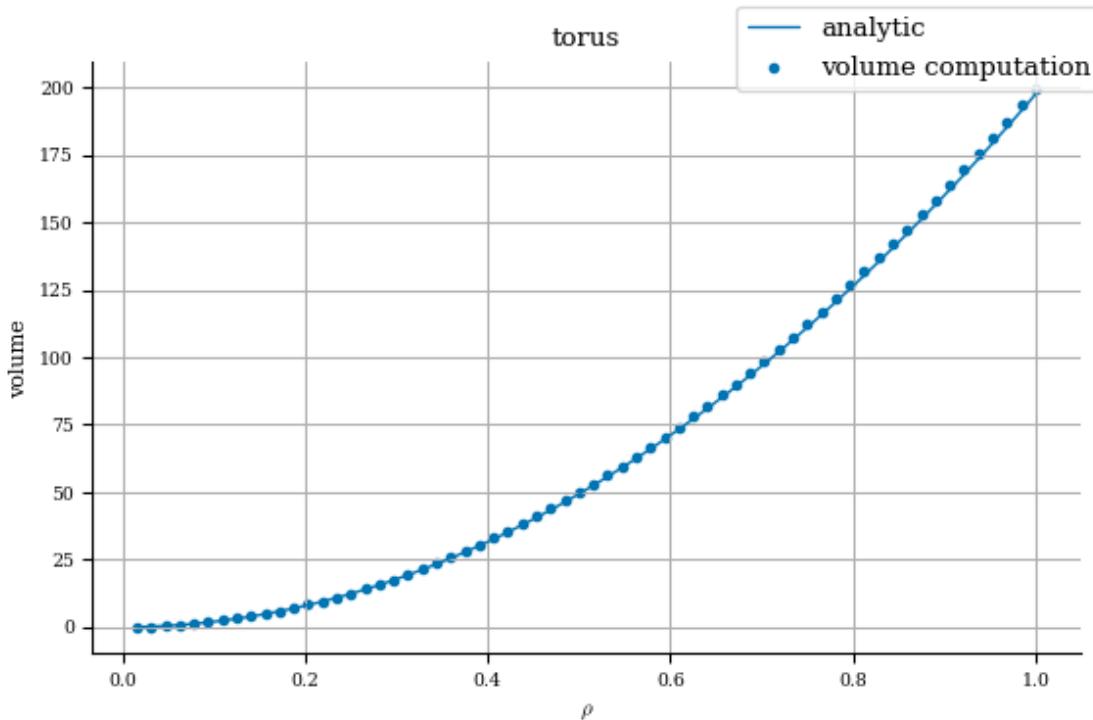
4 Magnetic well plots

Although the symmetry bug is fixed, forcing it off results in a closer match between the STELLOPT data and DESC 4.19 well. Here symmetry is not forced to false because I think its close enough.

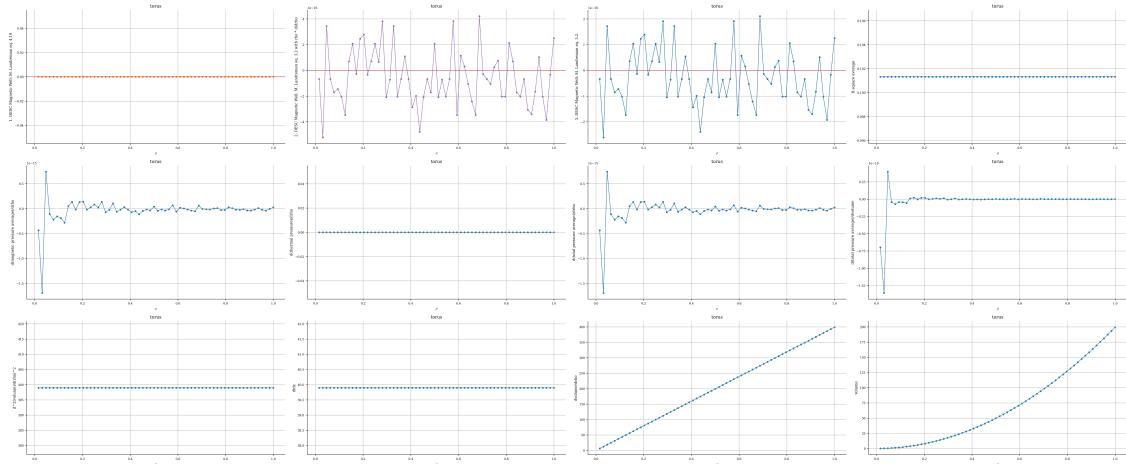
```
[8]: for s in stellarators:
    s.compute_plot()
```

```
[9]: # compare volume computation to known analytic case for torus
fig, ax = plt.subplots()
y = "volume"
rho, volume = torus.st[y]
ax.scatter(rho, volume, label=y + " computation", s=10)
ax.plot(rho, 20 * (np.pi * rho) ** 2, label="analytic")
ax.set(xlabel=r"\rho", ylabel=y, title=torus.name)
ax.grid()
fig.legend()
```

[9]: <matplotlib.legend.Legend at 0x7f46d7364be0>

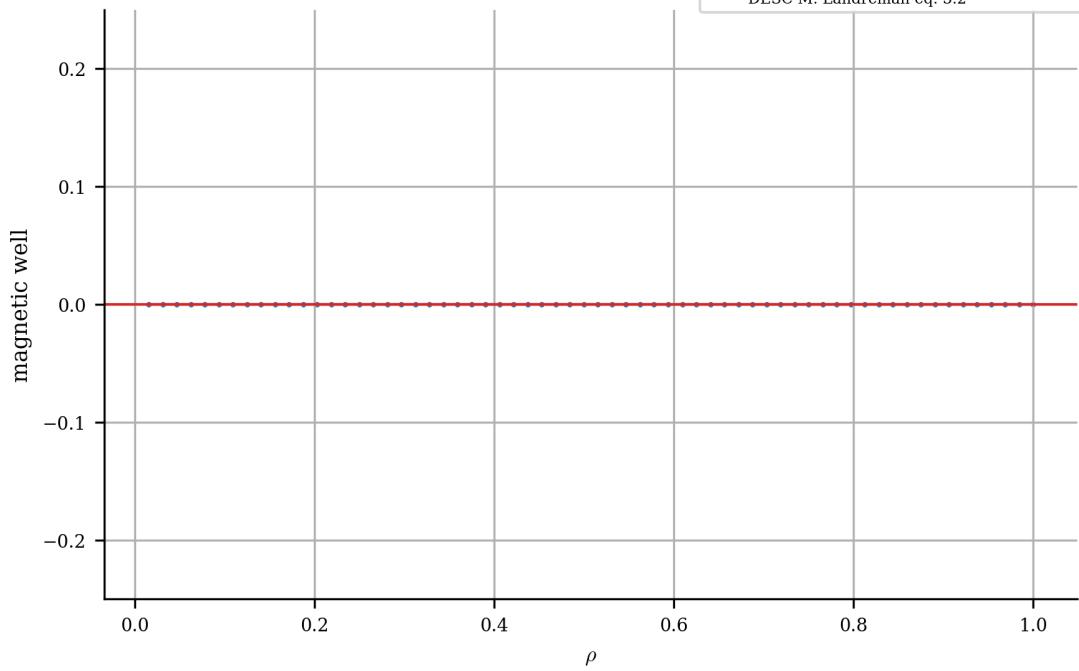


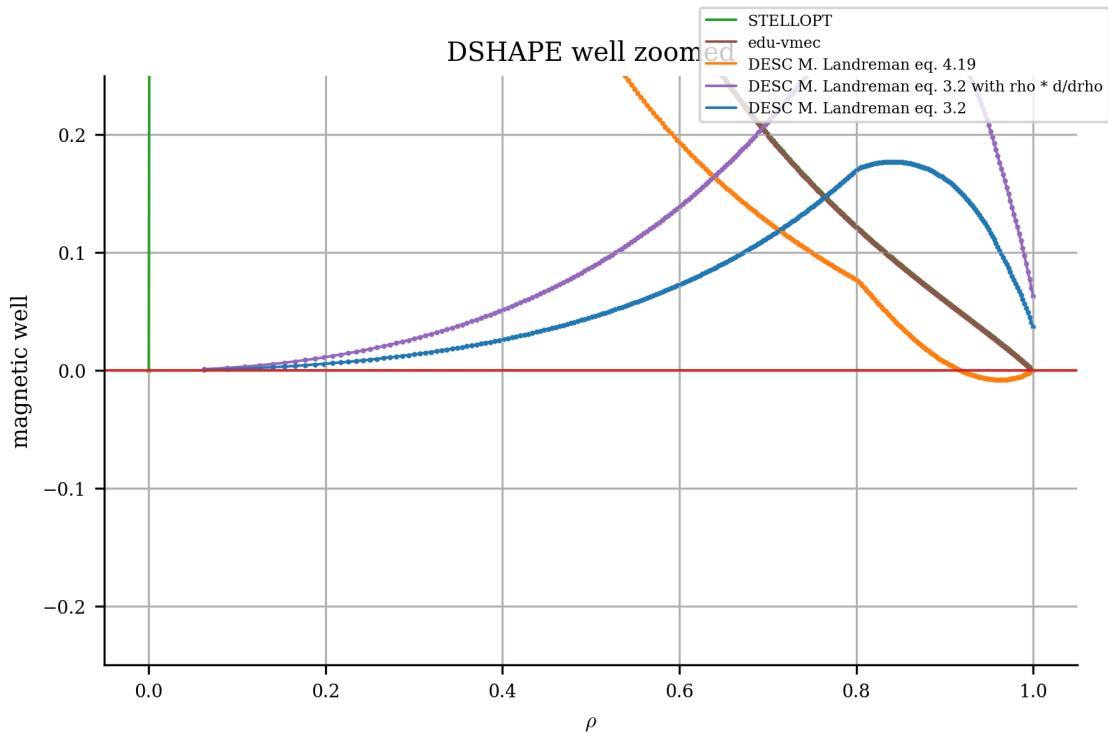
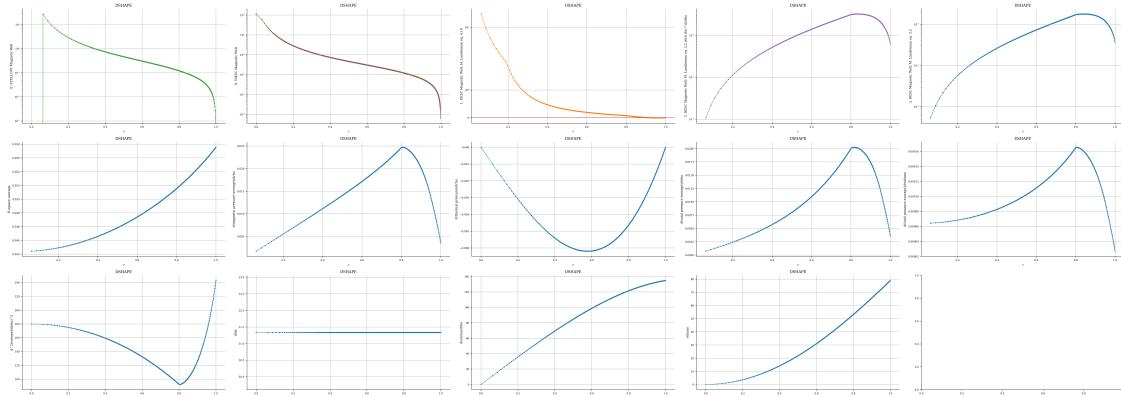
```
[10]: for s in stellarators:
    s.plot()
    s.plot_magnetic_wells()
```

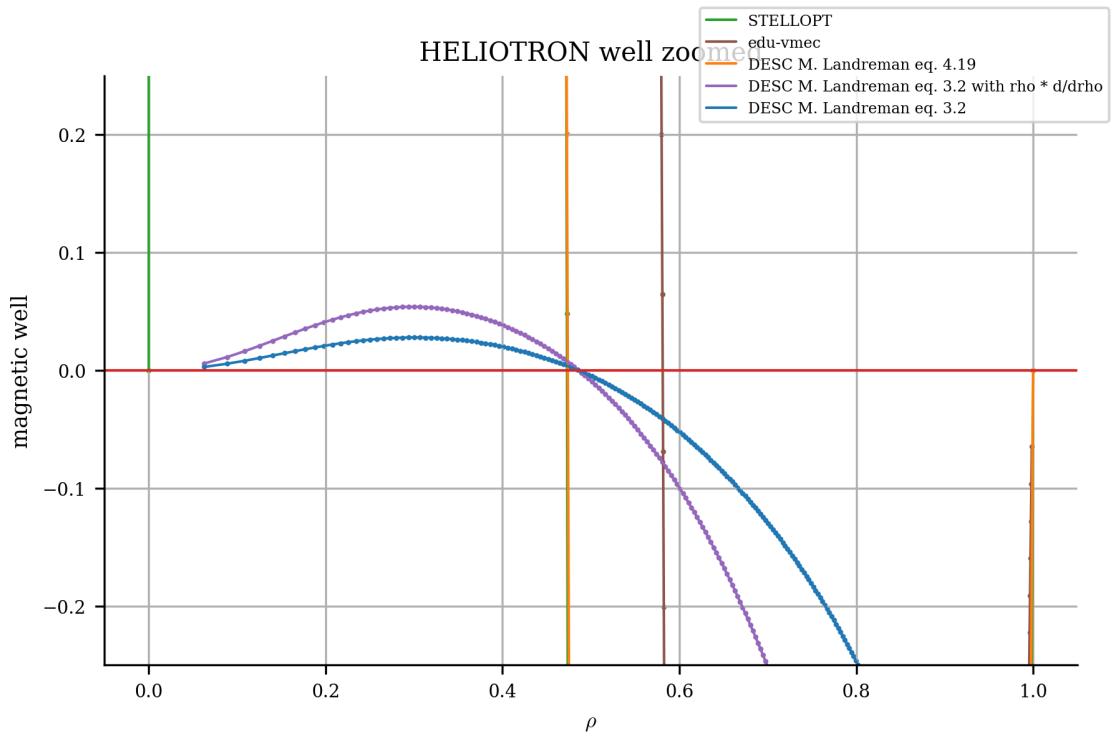
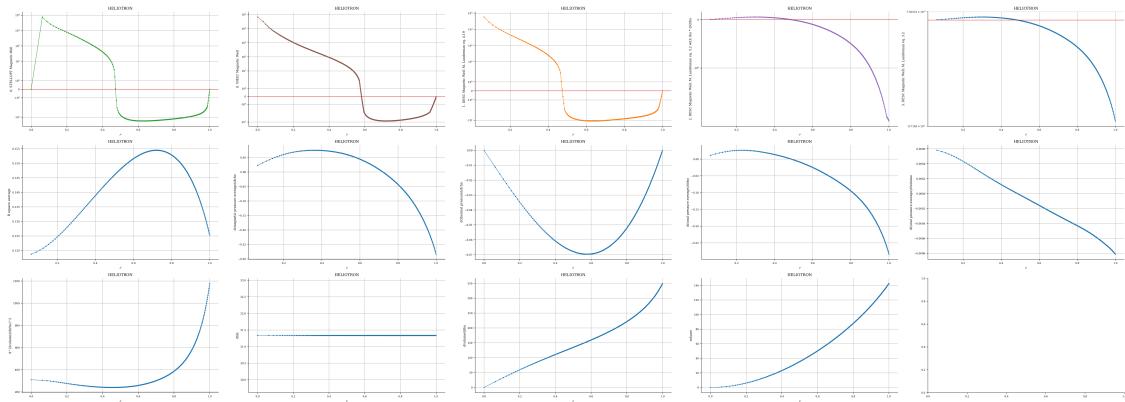


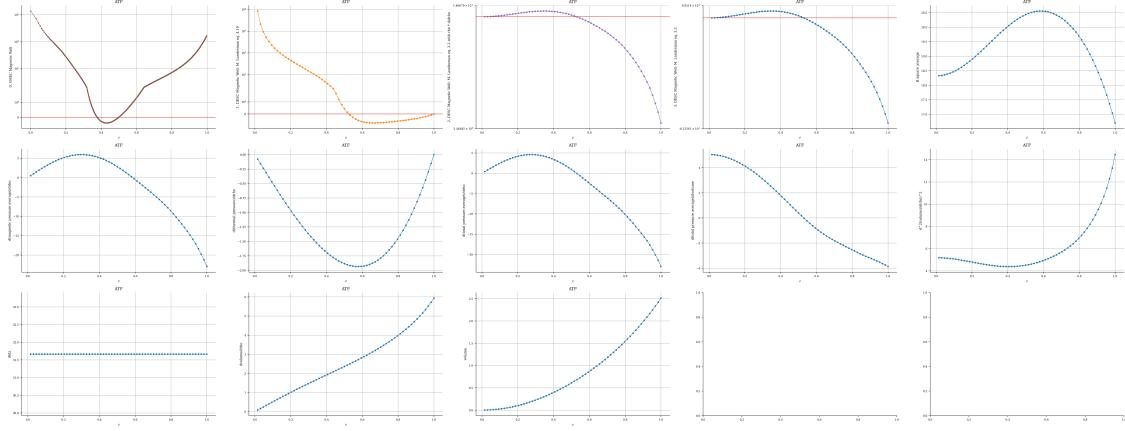
torus well zoomed

DESC M. Landreman eq. 4.19
DESC M. Landreman eq. 3.2 with $\rho * d/d\rho$
DESC M. Landreman eq. 3.2



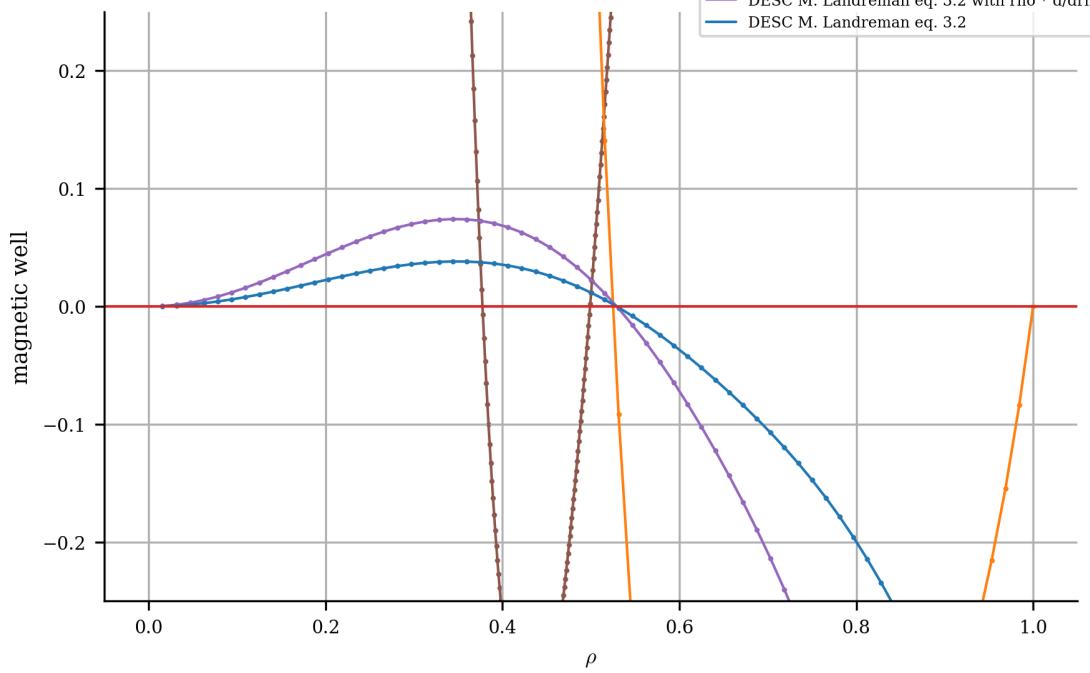


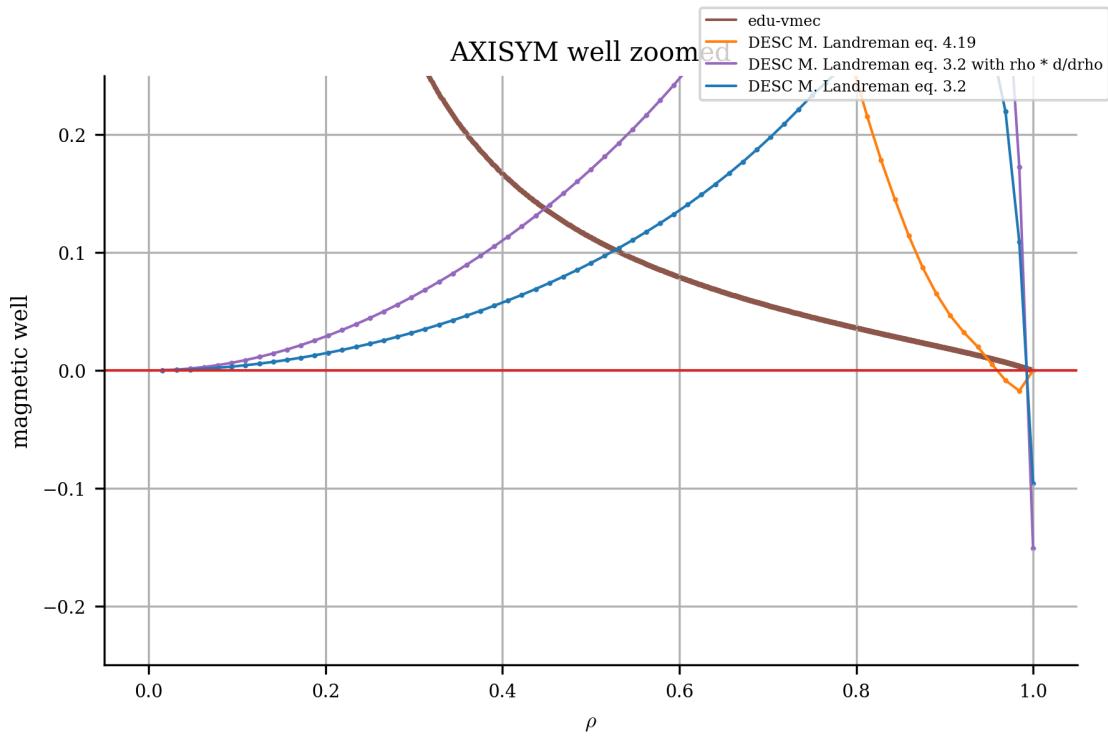
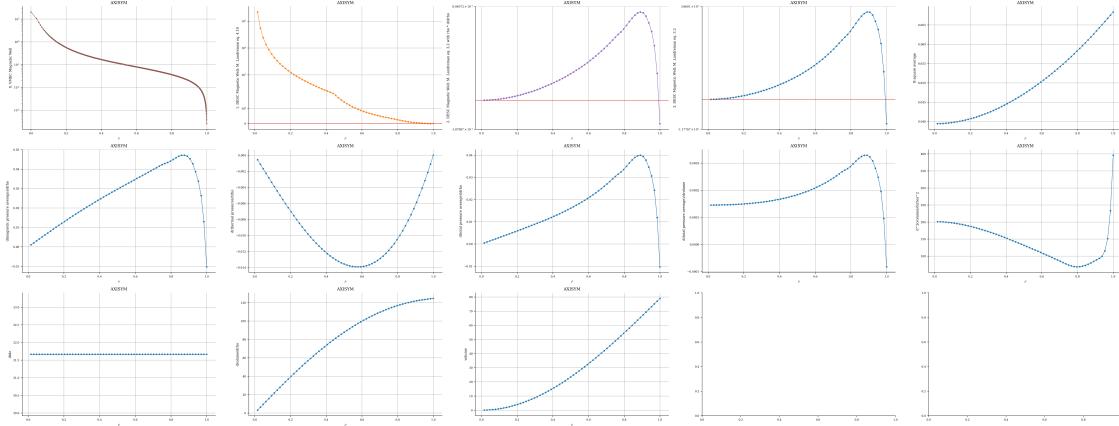




ATF well zoomed

	edu-vmec
	DESC M. Landreman eq. 4.19
	DESC M. Landreman eq. 3.2 with $\rho * d/d\rho$
	DESC M. Landreman eq. 3.2





4.1 Nice plot of Heliotron well

Turn symmetry off for closer match.

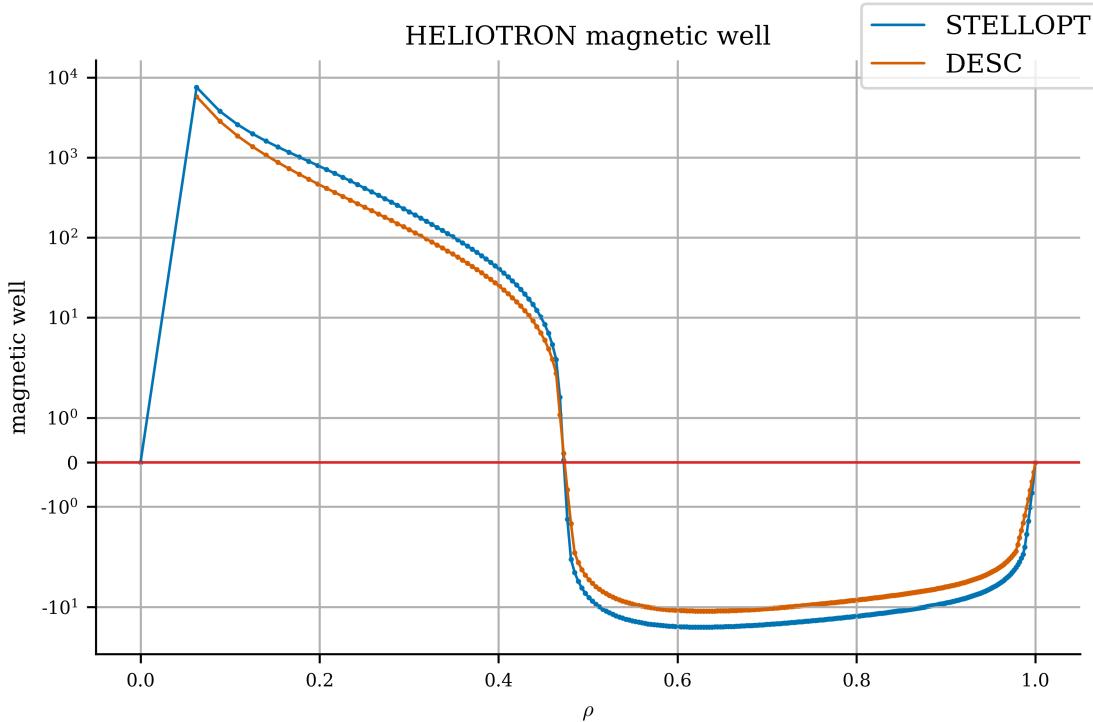
```
[11]: stellopt_rho, stellopt_well = heliotron.st["0. STELLOPT Magnetic Well"]
desc_well = heliotron.st["1. DESC Magnetic Well: M. Landreman eq. 4.19"] [1]
```

```
fig, ax = plt.subplots(dpi=600)
```

```

ax.plot(stellopt_rho, stellopt_well, label="STELLOPT")
ax.plot(heliontron.rho, desc_well, label="DESC")
ax.scatter(stellopt_rho, stellopt_well, s=1)
ax.scatter(heliontron.rho, desc_well, s=1)
ax.set(
   yscale="symlog",
 xlabel=r"$\rho$",
 ylabel="magnetic well",
 title=heliontron.name + " magnetic well",
 facecolor="white",
)
ax.axhline(color="tab:red")
ax.grid()
fig.legend()
fig.savefig("Heliontron STELLOPT vs DESC 4.19 sym true.png")

```



```
[12]: for s in stellarators:
    s.save()
```

5 Volume computation problem and solution

In `MagneticWell.compute()`, the volume computation relies on the quantity $d\theta * d\zeta$. This is obtained from splicing `grid.spacing`. The grid class takes advantage of things like reducing du-

plicated node weight, stellarator symmetry, and the number of field periods to reduce the amount of computation.

The problem is that, in the grid class's current implementation, the modifications made to `grid.spacing` to take advantage of symmetry and NFP do not preserve the value of $d\theta * d\zeta$. So independently plucking out $d\theta * d\zeta$ from a grid will not give the value its name implies.

Why is this? Because rescaling is done to preserve the full volume, or the weights ($d\rho * d\theta * d\zeta$) so that `grid.spacing.prod(axis=1).sum() = 4\pi^2`, at the expense of changing $d\theta * d\zeta$. Here's a visual:

```
[13]: # For any constant rho surface and NFP=1, grid.spacing is going
# to be an M*N length stack of the row vector (1, 2pi/M, 2pi/N).
g1 = LinearGrid(M=2, N=2, rho=np.array(1))
print(g1.spacing)
print()
# When NFP != 1, the values of drho are increased (decreased) while
# dtheta*dzeta decreases (increases).
# That's why the wrong volume was being computed for the heliotron with NFP > 1.
NFP = np.random.random_sample() * 100
print("NFP:", NFP)
g2 = LinearGrid(M=2, N=2, NFP=NFP, rho=np.array(1))
print(g2.spacing)

# the good thing is that the differential volume drho*dtheta*dzeta is preserved
# since that was the (main?) goal of the rescaling
assert np.allclose(g1.spacing.prod(axis=1), g2.spacing.prod(axis=1))
# and that, because rho=constant forces the drho vector to = 1 (with NFP=1),
# grid.weights is actually the value we expect from dtheta*dzeta (for any NFP).
if g1.num_rho == 1:
    assert np.allclose(g1.spacing.prod(axis=1), g1.spacing[:, 1:].prod(axis=1))
assert np.allclose(g1.spacing.prod(axis=1), g1.weights) # definition of weights
```

```
[[1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
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 [1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
 [1.0000 1.2566 1.2566]
```

5.1 Solution

On grids which are defined completely by a single rho surface (`grid.num_rho = 1`), the correct volume will be computed $\forall NFP \in \mathbb{R}^+$, if we take $d\theta * d\zeta$ to be `grid.weights` instead of `grid.spacing[:, 1:] . prod(axis=1)`.

On grids which are defined over a range of rho surfaces (`grid.num_rho != 1`) this will not work because $d\rho \neq 1$ on those grids. A general solution follows for computing the correct value for $d\theta * d\zeta$ to other grids $g \in Grid : g.num_rho \in \mathbb{N}$. * Let $g1 \in Grid : g1.NFP = 1$ and $g2 \in Grid : g2.NFP \in \mathbb{R}^+$. Then given $g2$, $d\theta * d\zeta = g2.weights / g1.spacing[:, 0]$. * I don't know how to retrieve $g1.d\rho$ from $g2$, other than storing it during grid construction. * Until this can

be fixed, any computation which requires differential surface elements (i.e. flux surface averages require the columns from `grid.spacing`) will yield incorrect quantities $\forall g \in Grid : g.num_rho \in \mathbb{N} \ 1$ and $g.NFP \in \mathbb{R}^+ \ 1$.

5.1.1 Edit: New grid fix for symmetry fixes the issue discussed below.

The last source of error in the volume is the stellarator symmetry boolean. `enforce_symmetry()` again modifies $d\theta * d\zeta$. Visual given below.

The error in computed volume that results from this is much smaller than the NFP error fixed above. The nodes with $\theta > \pi$ are removed and so too are the spacings in the grid that correspond to those nodes. Now because `grid.spacing` is missing these nodes, to preserve the overall volume in (ρ, θ, ζ) space (`grid.weights.sum()`), the differential volume $d\rho * d\theta * d\zeta$ of the remaining spaces is increased so that the sum is still $4\pi^2$. This makes sense since we do want to increase the weight of the nodes 0 to π to double count for the removed nodes. This process has preserving the volume $d\rho * d\theta * d\zeta$ in mind. It's not clear to me if a different scale factor (other than $4\pi^2$) would be better to preserve an area element $d\theta * d\zeta$. Might be dependent on ρ .

~~In any case, the solution implemented here is to force stellarator_symmetry to False. This is not ideal since it can simplify the computation of the transforms and such. An alternative could be to just recreate the grid with the nodes that were removed from `enforce_symmetry()` in the `MagneticWell` class and use this grid just for the volume computation. This could allow the grid with symmetry to still be used elsewhere.~~

```
[14]: g3 = LinearGrid(M=2, N=2, sym=True, rho=np.array(1))
print(g3.spacing)
```

```
[[1.2599 1.3194 1.5833]
 [1.2599 1.3194 1.5833]
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 [1.2599 1.3194 1.5833]
 [1.2599 1.3194 1.5833]
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 [1.2599 1.3194 1.5833]
 [1.2599 1.3194 1.5833]]
```