September 4, 2019 Matt Landreman

Comparing the permanent magnet thickness to make various stellarator configurations

In this note we consider a database of 13 stellarator configurations. The database includes the 6 QA configurations and 4 QH configurations from Landreman PPCF 61, 075001 (2019), as well as the Aten and QHS46 configurations (both QH) from the Wisconsin group, and W7-X. (For W7-X I use a fixed-boundary case free of coil ripple, representative of the configuration targeted in the 1990s coil design, provided by Drevlak). All configurations are scaled in size so vmec's Rmajor_p parameter is 1.442 m, the same as for NCSX c09r00. For HSX, the modular ripple is removed by Fourier-filtering the boundary shape. For simplicity, pressure and current are set to 0 in all configurations (keeping the boundary shape fixed.)

We then carry out REGCOIL_PM calculations for each configuration. We assume the magnetic field is produced by a purely toroidal field plus the permanent magnets, i.e. there is no optimization of the orientation of the planar TF coils. The same net poloidal current, 3.91e+6 Amperes, is used for all configurations, corresponding to an on-axis field of ~0.5 T. For each configuration, we consider an inner permanent magnet surface obtained by a uniform 8 cm separation from the vmec boundary. This value was chosen because the NCSX vacuum vessel had a distance of closest approach to the vmec boundary of ~8 cm. The REGCOIL_PM regularization parameter λ is set separately for each configuration such that the maximum B_{normal} = 3.244e-3 T, which is the value obtained in the previous REGCOIL_PM NCSX 0.5T calculation with ports that was circulated with this group, and in which free-boundary reconstructions were known to be good. Without detailed free-boundary studies for each configuration, I am not certain that this way to set λ is great in all cases, but it is a reasonable first guess.

The results of the REGCOIL_PM study are summarized in the following table:

Configuration	Aminor_p (m)	Plasma aspect ratio	Max PM thickness (cm)	Volume of PM (m^3)	Max PM thickness / Aminor_p
NCSX (c09r00)	0.323	4.46	8.8	1.11	0.27
Nuhrenberg-Zille	0.123	11.72	10.2	0.52	0.83
HSX	0.145	9.94	11.7	0.94	0.81
KuQHS48	0.178	8.10	Failed	Failed	Failed
Drevlak QH	0.168	8.58	Failed	Failed	Failed
ARIES-CS	0.317	4.55	10.9	1.26	0.34
Garabedian QAS2	0.555	2.60	24.6	2.99	0.44
ESTELL	0.272	5.30	7.9	0.69	0.29
CFQS	0.333	4.33	17.1	1.96	0.51
Henneberg QA	0.427	3.38	19.3	2.5	0.45
Aten	0.215	6.71	17	1.62	0.79
QHS46	0.215	6.71	17.3	1.7	0.80
W7-X	0.138	10.45	6.9	0.4	0.50

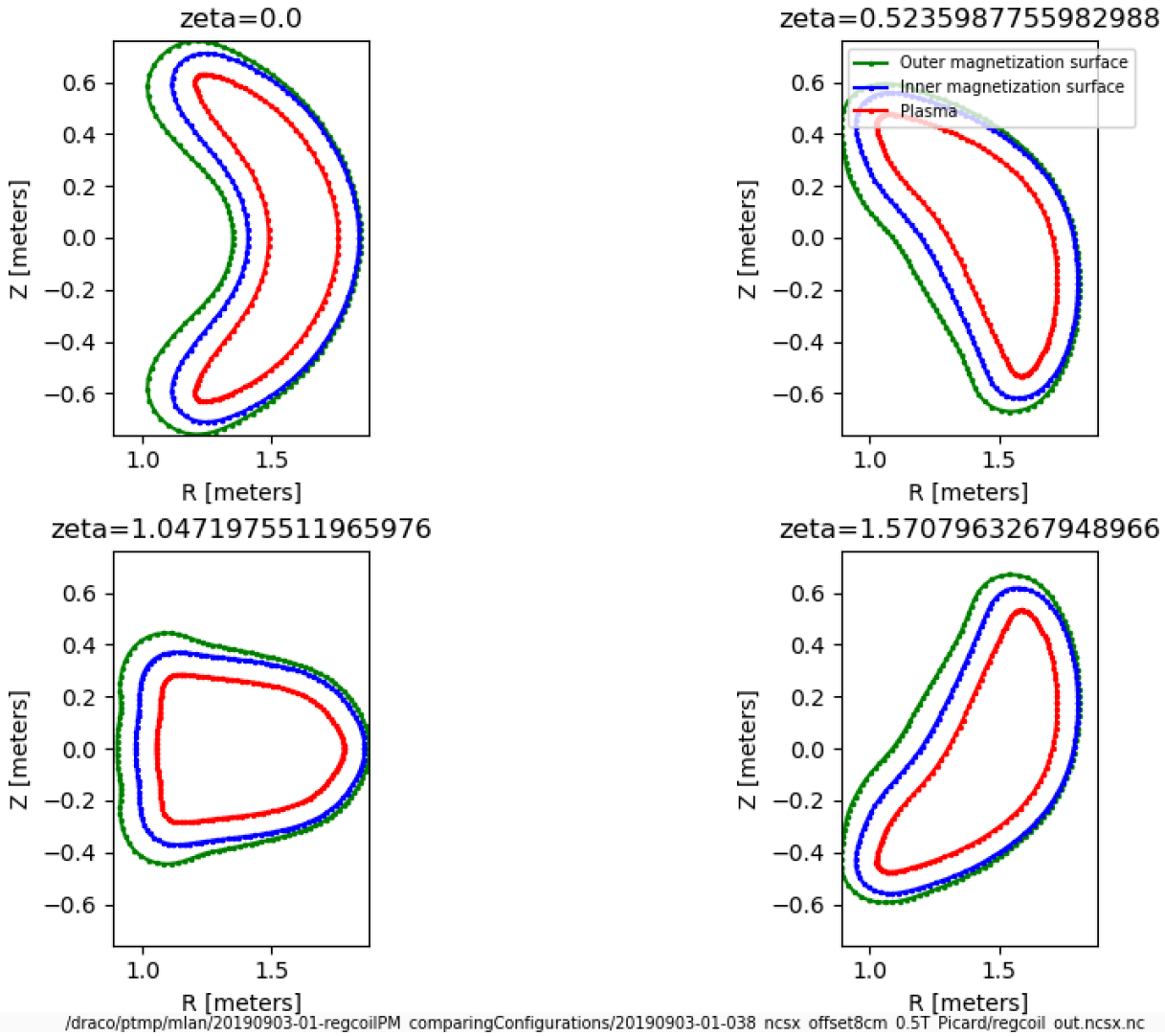
The KuQHS48 and DrevlakQH cases failed because the surface radius of curvature was < 8 cm, making it impossible to construct the boundary surface.

Several features of the results are noteworthy. The configurations that require the thinnest PM layer are NCSX, ESTELL, and W7-X. QAS2 requires the thickest PM layer, but this is likely related to the fact that it has the largest minor radius (aspect ratio = 2.6). Therefore another natural metric is the right column of the table: the PM thickness normalized to the plasma minor radius. By this measure, NCSX and ESTELL are the easiest configurations to produce, while W7-X and QAS2 are in the middle of the pack. It is not surprising that ESTELL requires the thinnest permanent magnet layer, since it has low iota (0.2). Several QH configurations (Nuhrenberg-Zille and HSX) require just slightly thicker PM than NCSX in absolute length, but when normalized to the plasma minor radius, the QH configurations all require significantly thicker permanent magnets than the QA and QI configurations. ARIES-CS is a bit harder to produce than NCSX. The overall conclusion seems to be that NCSX is the best configuration to consider, unless we want to consider lowering iota.

The assumption of a purely toroidal field from the electromagnets is appropriate for the SAS design, since the NCSX TF coils will probably be used, but it could be relaxed for other designs. The nfp=2 QA configurations (QAS2, ESTELL, CFQS, Henneberg) all have magnetic axis shapes which are elliptical rather than circular. The axis shapes of the QH configurations depart even more strongly from a circle. Therefore, for these configurations, the PM thickness may be substantially reduced if the TF coils have optimized locations.

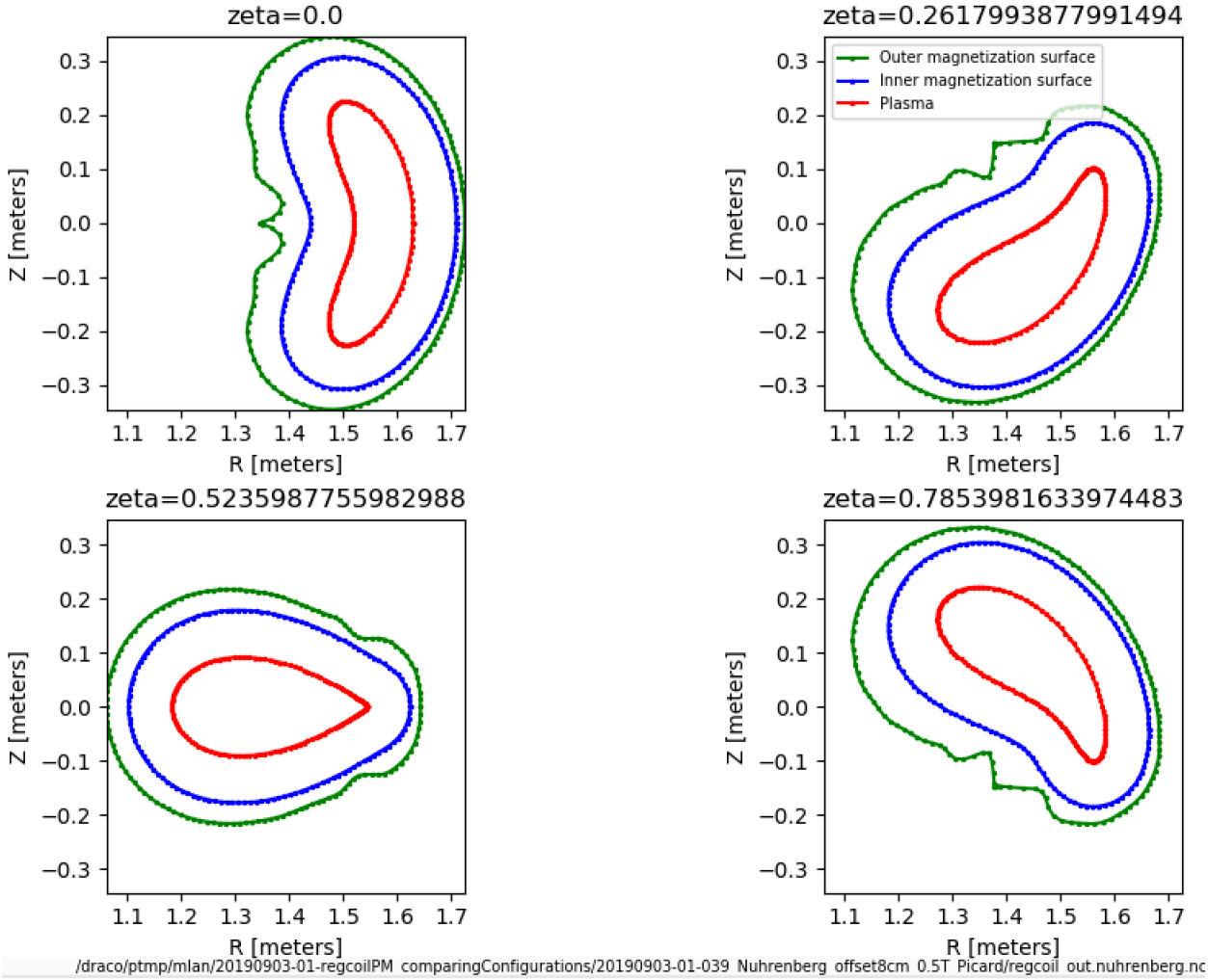
Below are figures displaying the results for all the configurations.

NCSX



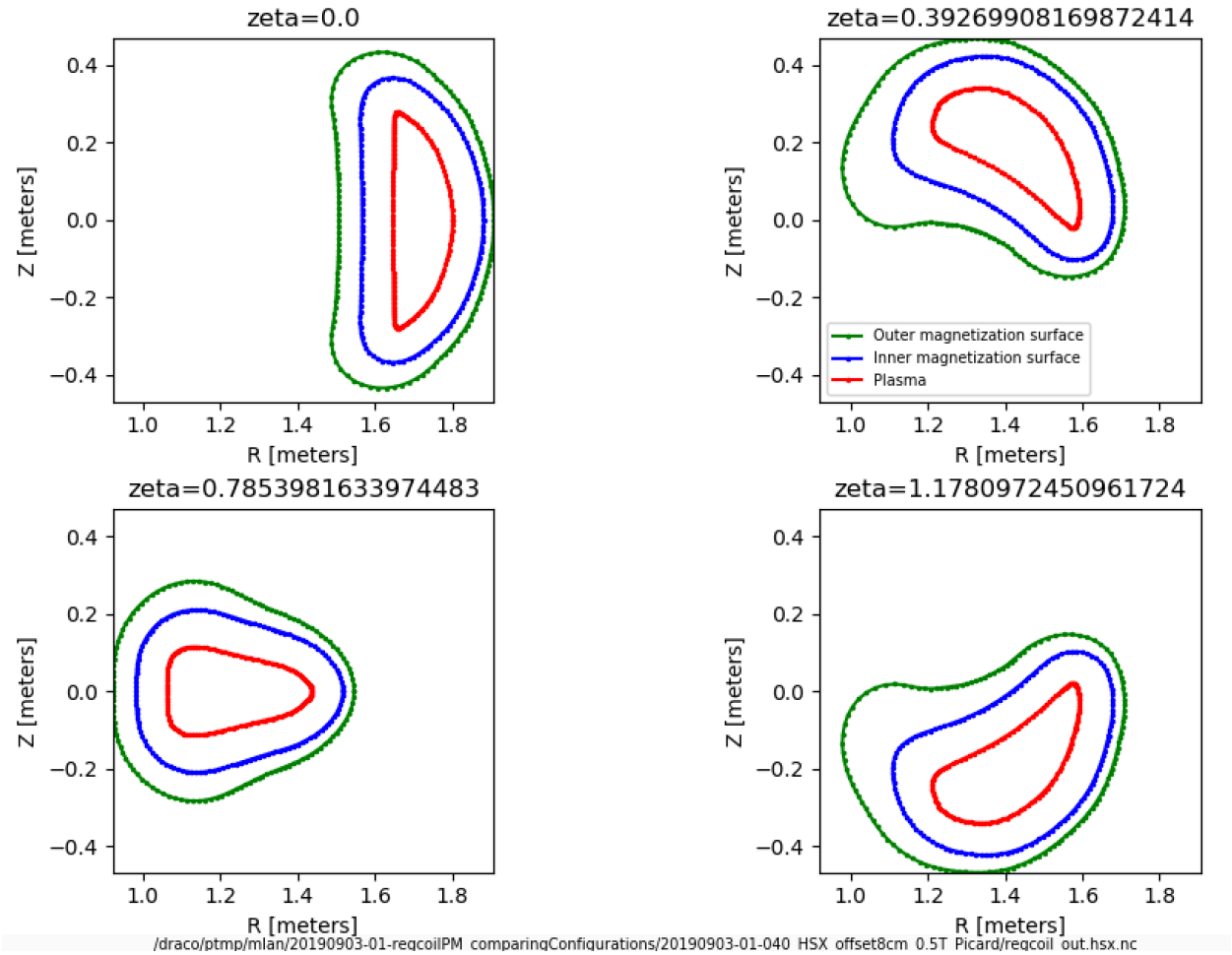
/draco/ptmp/mlan/20190903-01-regcoilPM comparingConfigurations/20190903-01-038 ncsx offset8cm 0.5T Picard/regcoil out.ncsx.nc

Nuhrenberg-Zille



The sharp structure in the PM thickness for this case might be a numerical artifact…

HSX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R [meters]
Outer magnetization surface
Inner magnetization surface
Plasma
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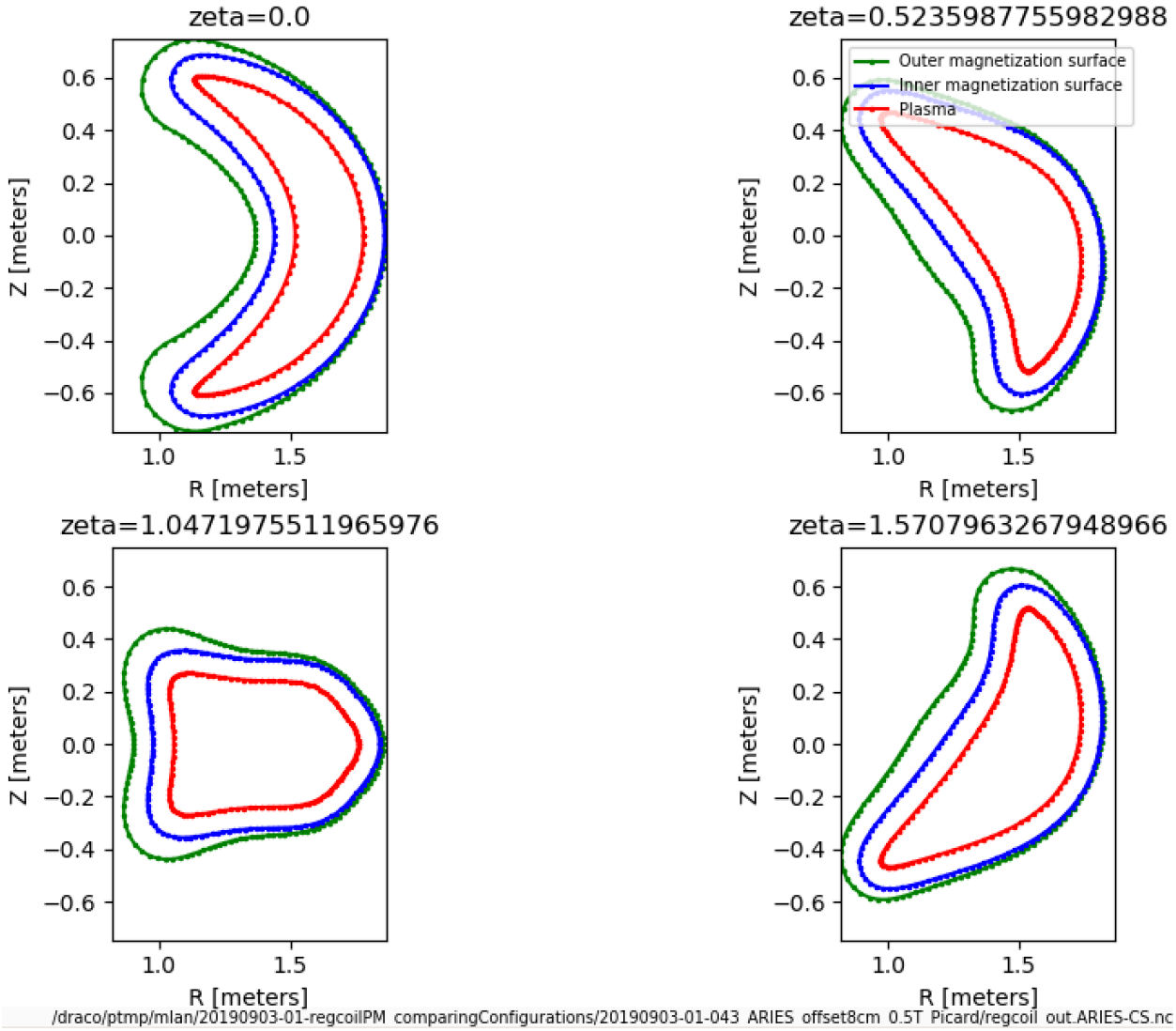
ARIES-CS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1.5
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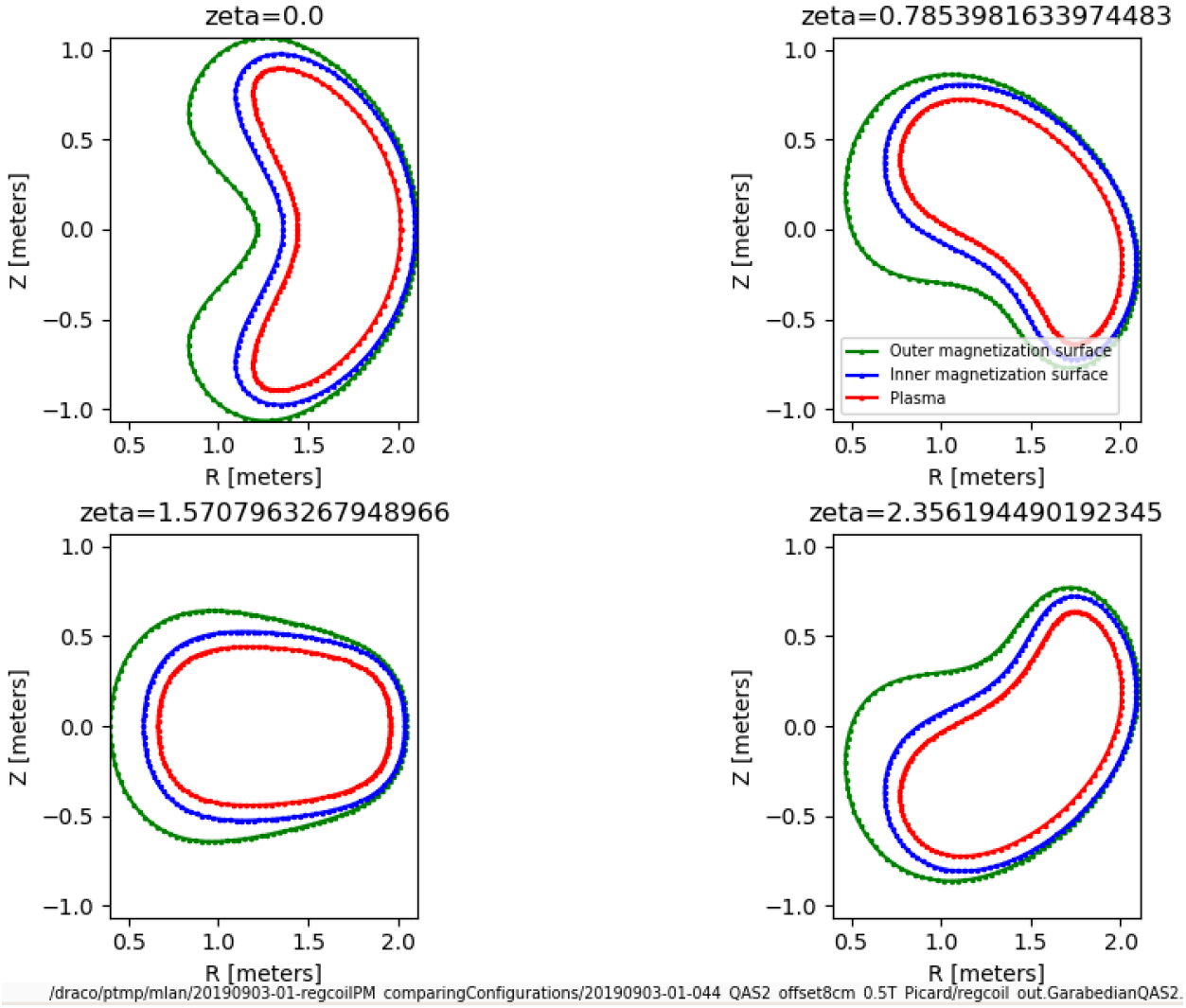
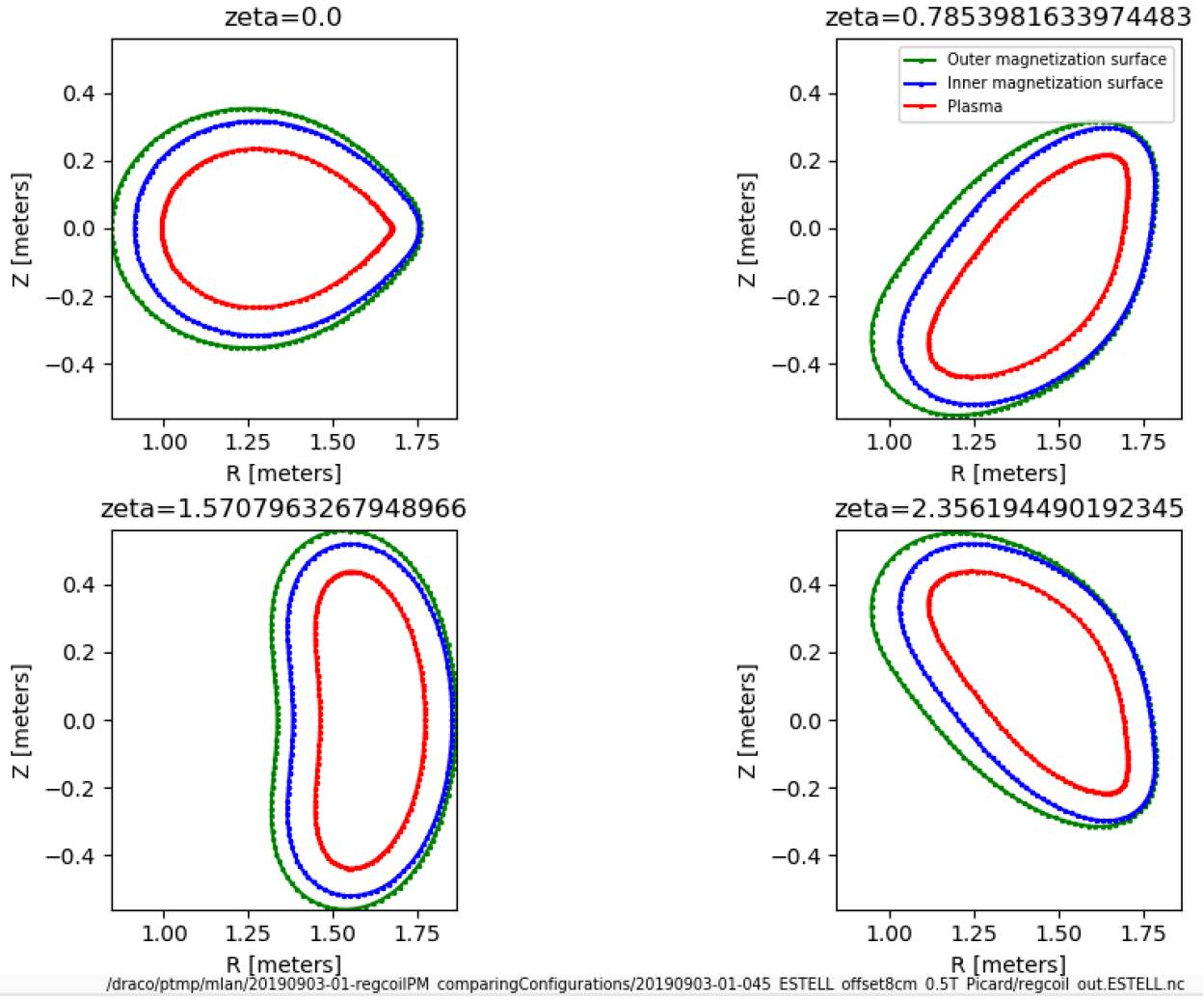
Garabedian QAS2



ESTELL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Outer magnetization surface
Inner magnetization surface
Plasma
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R [meters]
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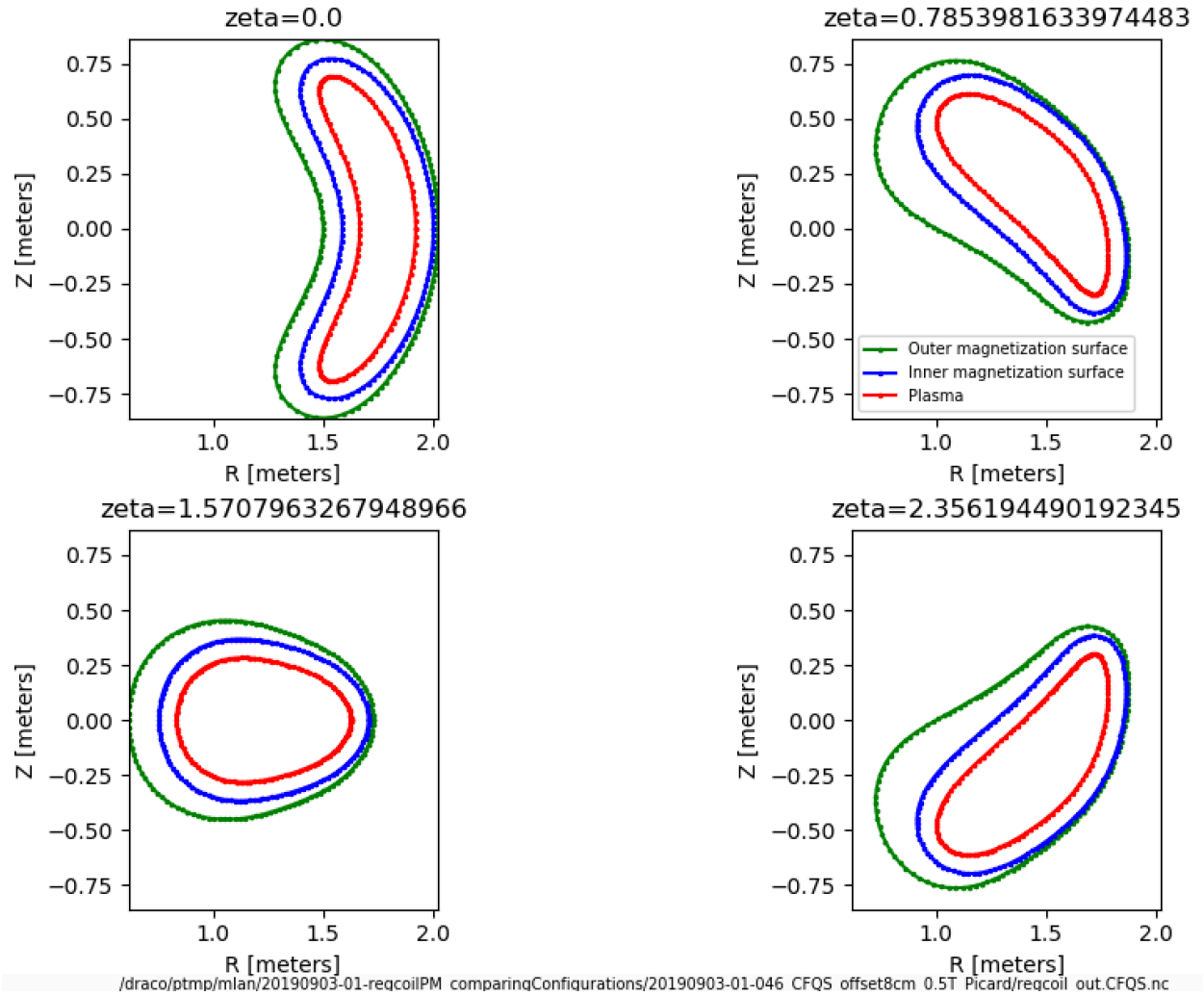
CFQS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Outer magnetization surface
Inner magnetization surface
Plasma
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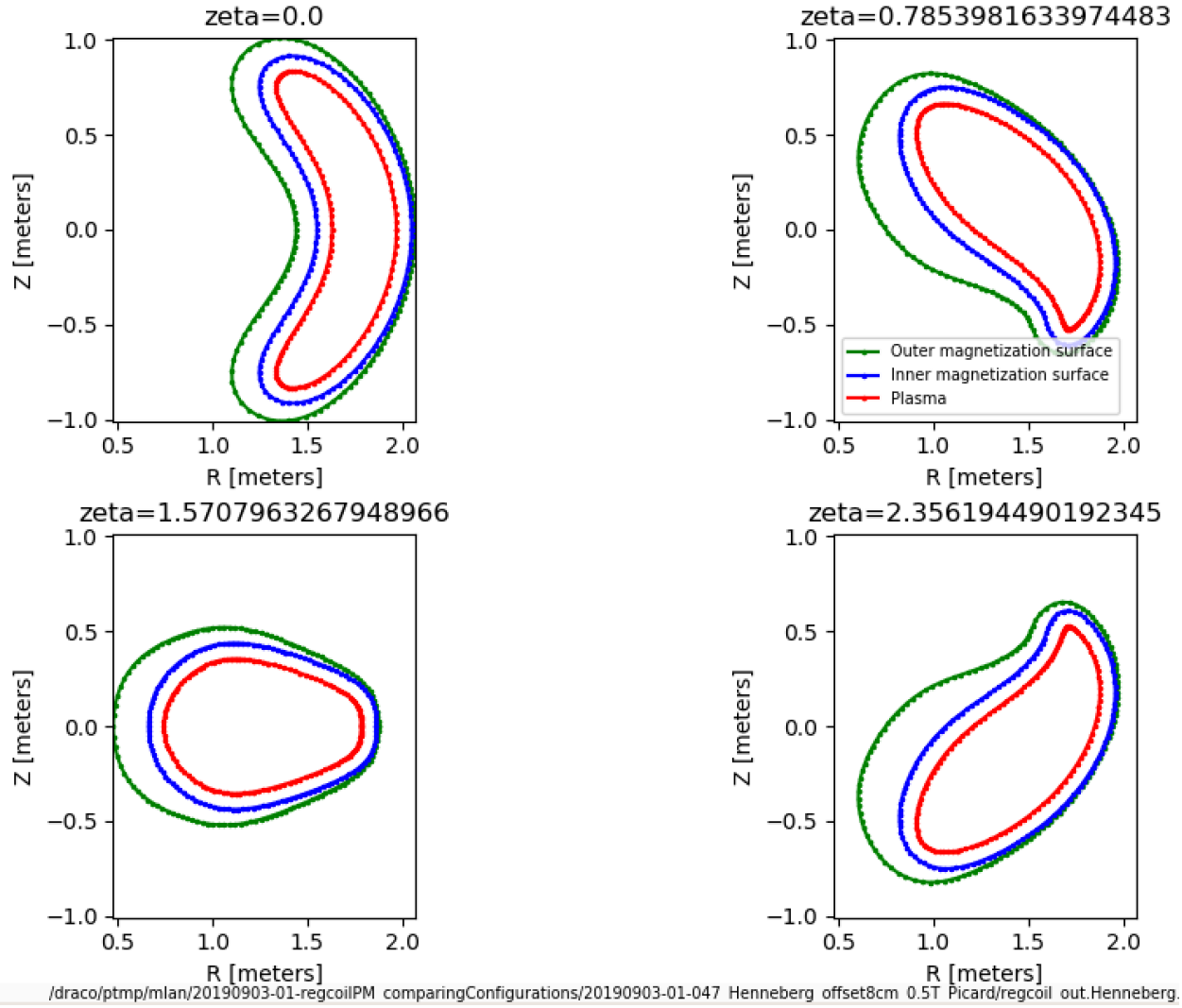
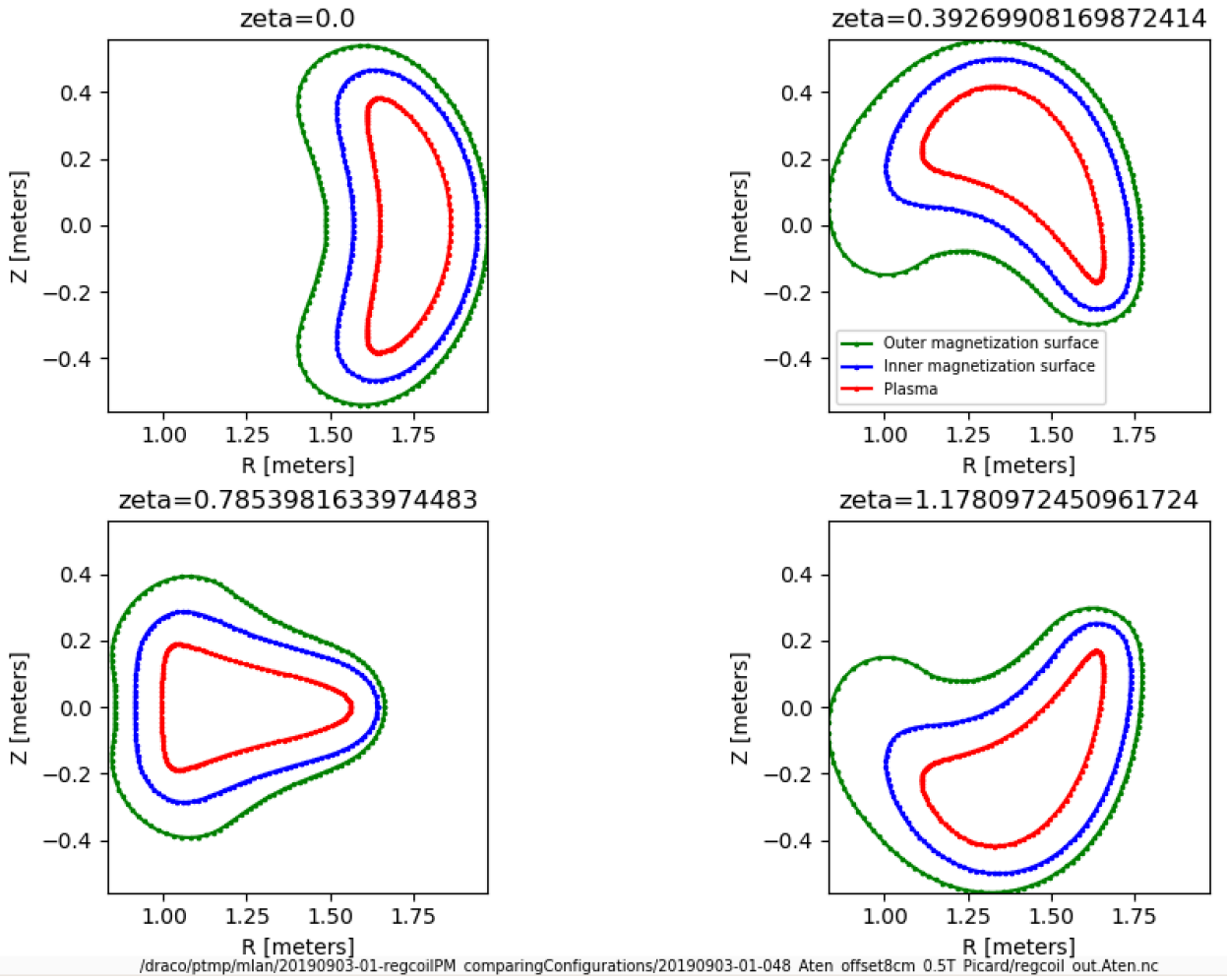
Henneberg QA



Aten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0.2
0.0
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−0.4
1.00
1.25
1.50
1.75
Outer magnetization surface
Inner magnetization surface
Plasma
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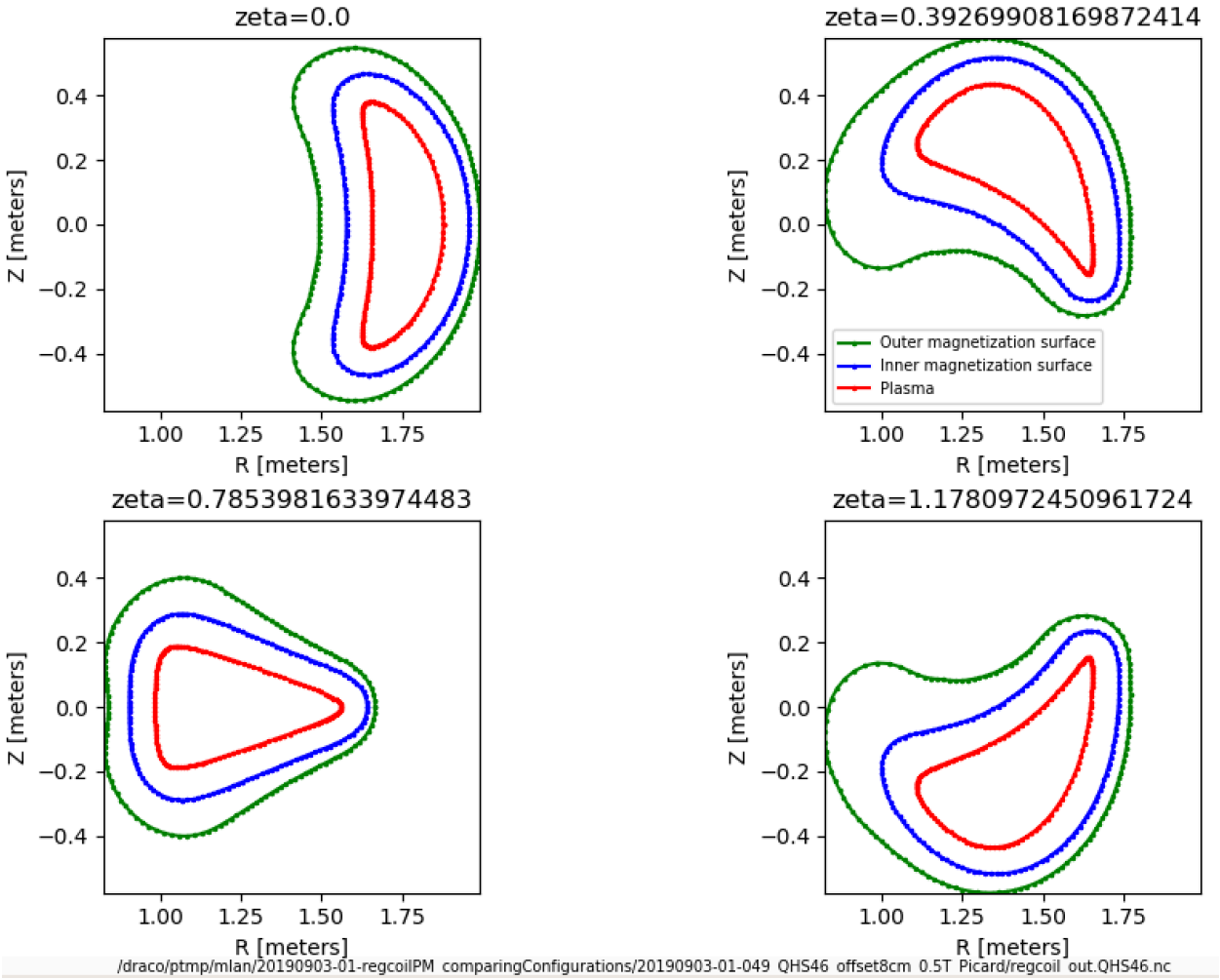
QHS46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R [meters]
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0.2
0.0
−0.2
−0.4
1.00
1.25
1.50
1.75
Outer magnetization surface
Inner magnetization surface
Plasma
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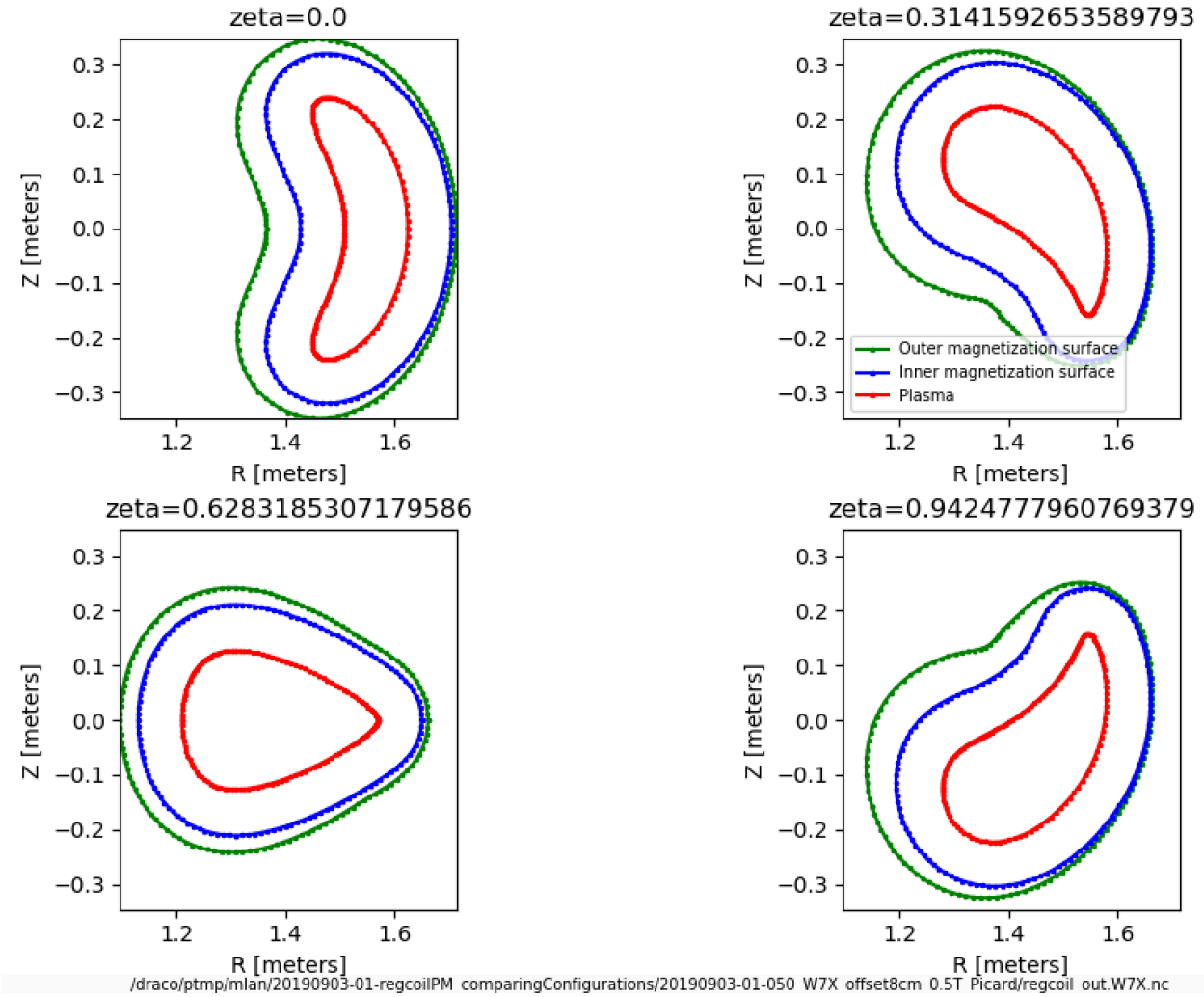
W7-X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Outer magnetization surface
Inner magnetization surface
Plasma
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