Exercise - Control and operation of tokamaks 2025

Topic: Free boundary equilibrium, FBT & LIUQE reconstruction

Prerequisite: Path setup

```
% Add the MEQ base directory to the MATLAB path
meqdir = fullfile(pwd);
addpath(meqdir);

% The TCV geometry and experimental data is provided via MAT-files,
% download and extract them then add their location to the MATLAB path
datdir = fullfile(pwd,'tcv_files_ex4');
addpath(datdir);

% Check that all necessary files are accessible
meqpath('fbt','file');
meqpath('liu','file');
```

For generating .pdf figures outputs select print_figures = true

```
print_figures = false;
```

Exercise 1 - Design of the vacuum equilibrium field

```
% Input equilibrium parameters
Ip = -400e3;    % [A] total plasma current
kappa = 1.6;    % [-] Elongation
betap = 0.3;    % [-] Poloidal beta
li = 1;         % [-] internal inductance
a = 0.25;       % [m] Plasma minor radius
r0 = 0.87;      % [m] R position of plasma axis
z0 = 0;         % [m] Z position of the plasma axis

% Required parameters
n = -1.44;      % field index
Br0 = 0;        % Br component on axis
```

Compute required contraints

```
Bz0 = -mu0*Ip/4/pi/r0*(log(8*r0/a/sqrt(kappa)) + betap + li/2 - 3/2); % Bz
component on axis
dBz0dr = -n * Bz0 / r0; % Derivative of Bz componet on axis
```

Green's function's from function exgf

```
prefix = 'tcv_102735_fbt';
```

```
fileargs = {'pfile',[prefix,'_P'],'gfile',[prefix,'_G'],'xfile',
[prefix,'_X']};
[L,~,LY] = fbt('file',102735,[],fileargs{:});
```

```
FBTX cost function / constraints display
  Tokamak: TCV, shot#102735, t=0.010

Coil current  cost / equality constraints:
E_001              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_002              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_003              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_004              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_005              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_006              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_007              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_008              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
F_001              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_002              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_003              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_004              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_005              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_006              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_007              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_008              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]

Coil current  combination cost / equality constraints:
   none

Dipole  cost / equality constraints:
   none

Coil current limits:
-7.50e+03[A] <=     +1*E_001   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_002   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_003   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_004   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_005   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_006   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_007   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_008   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_001   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_002   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_003   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_004   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_005   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_006   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_007   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_008   <= +7.50e+03[A]
-1.05e+04[A] <=     +1*F_001    -1*F_002  -0.5*F_003 -0.25*F_004 <= +1.05e+04[A]
-1.05e+04[A] <=   +0.5*F_001    +1*F_002    -1*F_003  -0.5*F_004 -0.25*F_005 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_001  +0.5*F_002    +1*F_003    -1*F_004  -0.5*F_005 -0.25*F_006 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_002  +0.5*F_003    +1*F_004    -1*F_005  -0.5*F_006 -0.25*F_007 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_003  +0.5*F_004    +1*F_005    -1*F_006  -0.5*F_007 -0.25*F_008 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_004  +0.5*F_005    +1*F_006    -1*F_007  -0.5*F_008 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_005  +0.5*F_006    +1*F_007    -1*F_008 <= +1.05e+04[A]
-4.00e+04[A] <=   +2.1*E_001  +1.1*E_002 +0.67*E_003 +0.21*E_004 -0.21*E_005 -0.67*E_006  -1.1*E_007  -2.1

Passive currents cost / equality constraints:
   none

Coil voltage  cost / equality constraints:
   none

Coil voltage limits:
```

```
   none

Magnetic geometry  cost / equality constraints:
r=+1.114 z=+0.000        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+1.095 z=+0.121        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+1.042 z=+0.230        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.967 z=+0.317        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.883 z=+0.373        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.804 z=+0.392        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.737 z=+0.373        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.685 z=+0.317        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.651 z=+0.230        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.630 z=+0.121        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.624 z=+0.000        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.630 z=-0.121        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.651 z=-0.230        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.685 z=-0.317        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.737 z=-0.373        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.804 z=-0.392        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.883 z=-0.373        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.967 z=-0.317        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+1.042 z=-0.230        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+1.095 z=-0.121        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]

Plasma profile constraints:
Ip         iD=1 LX.(Ip)(01)=-4e+05
qA         iD=1 LX.(qA)(01)= 0.95
fbtlegacy  iD=1
 tok    shot   kit     t[s]   Ip[kA]    bp    li  nA    rA[m]    zA[m]   dz[mm]     k      tol  resmaxF res
=============================================================================================================
file 102735     0   0.0100  -400.00  0.00  0.00   1   0.8848  -0.0001  +0.0000  1.62 2.00e-04      NaN
file 102735     1   0.0100  -400.00  0.23  1.12   1   0.8821  -0.0000  +0.0000  1.62 2.00e-04 1.66e+00
file 102735     2   0.0100  -400.00  0.19  0.96   1   0.8810  -0.0000  +0.0000  1.62 2.00e-04 2.34e-01
file 102735     3   0.0100  -400.00  0.19  0.95   1   0.8807  -0.0000  +0.0000  1.62 2.00e-04 6.22e-02
file 102735     4   0.0100  -400.00  0.19  0.95   1   0.8805  -0.0000  +0.0000  1.62 2.00e-04 1.77e-02
file 102735     5   0.0100  -400.00  0.19  0.95   1   0.8805  -0.0000  +0.0000  1.62 2.00e-04 5.23e-03
file 102735     6   0.0100  -400.00  0.19  0.95   1   0.8805  -0.0000  +0.0000  1.62 2.00e-04 1.58e-03
file 102735     7   0.0100  -400.00  0.19  0.95   1   0.8805  -0.0000  +0.0000  1.62 2.00e-04 4.89e-04
file 102735     8   0.0100  -400.00  0.19  0.95   1   0.8805  -0.0000  +0.0000  1.62 2.00e-04 1.54e-04
```

```
[Mxa,Brxa,Bzxa,~,Brpa,Bzpa,Cpa,na] = exgf(L.G,r0, z0);
rx = L.G.rx; zx = L.G.zx;
nr = numel(rx); nz = numel(zx);
```

1.a Solve LSQ problem

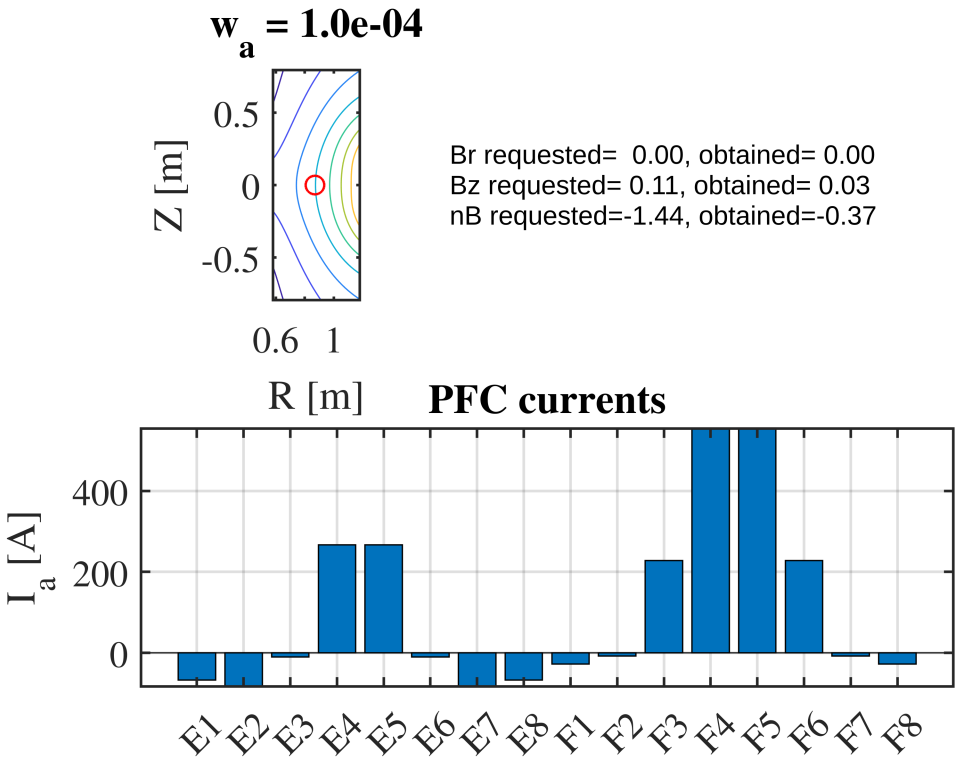
The minimization problem can be brought in the form $\min_x \|Ax - b\|_2^2$, as can be seen below in the LSQ setup.

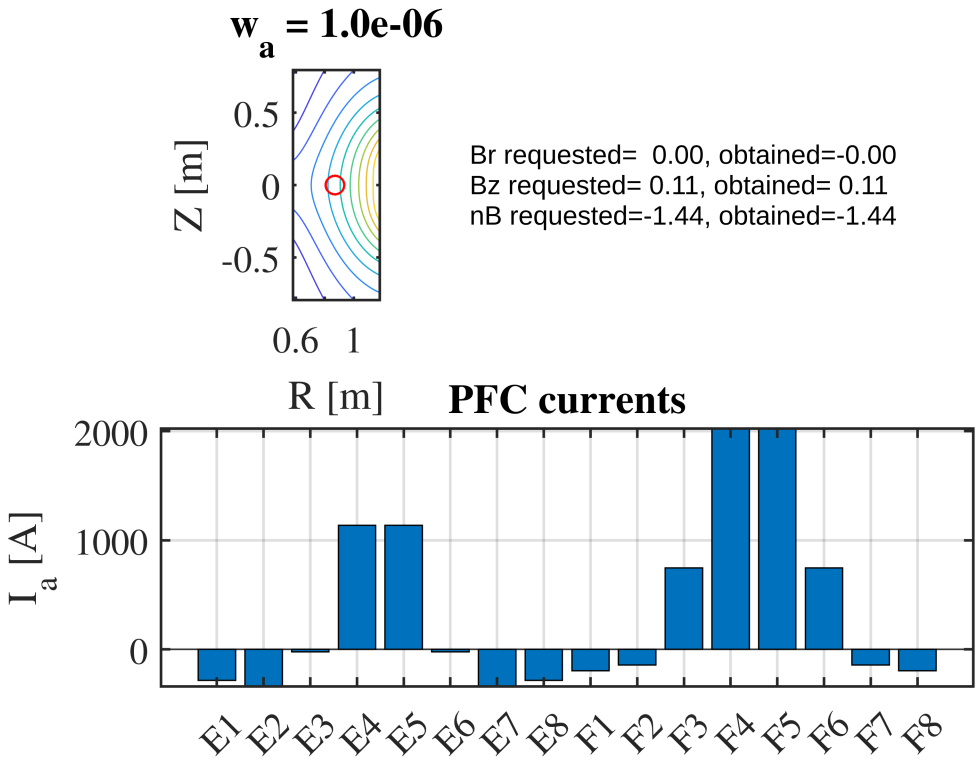
The weight wa measures the relative importance in the cost function of respecting the magnetic field/curvature against minimizing the current amplitude: higher weight means smaller current but worse matching of the B/ curvature requirements. Set here the current weights for LS minimization and vary to analyse their impact.

```
wa = [1e-4,1e-6];
```

Set up LSQ problem:

```
for ii = 1:length(wa)
  A = [Brpa ; Bzpa; Cpa; eye(na)*wa(ii)];
  b = [Br0; Bz0; dBz0dr; zeros(na,1)];

  % Solve using Matlab \ operator, this is equivalent of solving (A'A) Ia =
A'b
  Ia_lsq = A\b;

  % Obtain magnetic field results
  Brq_lsq = Brpa*Ia_lsq;
  Bzq_lsq = Bzpa*Ia_lsq;
  nBq_lsq = -r0 / Bz0*(Cpa*Ia_lsq);

  % Obtain flux, reshape on rz-grid
  psi_lsq = reshape(Mxa* Ia_lsq, [nz,nr]);

  % Plot results:
  fig = figure;
  subplot(2,2,1) % flux map
  contour(rx,zx,psi_lsq); hold on; plot(r0,z0,'ro');
  title(sprintf('w_a = %1.1e',wa(ii)) ), xlabel('R [m]'), ylabel('Z [m]'),
axis equal

  text(1.75, 0, sprintf(' Br requested= %5.2f, obtained=%5.2f \n Bz
requested=%5.2f, obtained=%5.2f \n nB requested=%5.2f, obtained=%5.2f',...
    Br0,Brq_lsq,Bz0,Bzq_lsq,n,nBq_lsq))

  subplot(2,2,[3,4]) % coil currents
  bar(Ia_lsq); title('PFC currents');
  ylabel('I_a [A]');
  set(gca,'xtick',1:16,'xticklabel',
[num2str((1:8)','E%d');num2str((1:8)','F%d')],'xgrid','on');

  if print_figures
    print_pdf(fig, sprintf('lsq_wa%1.1e.pdf',wa(ii)));
  end
end
```





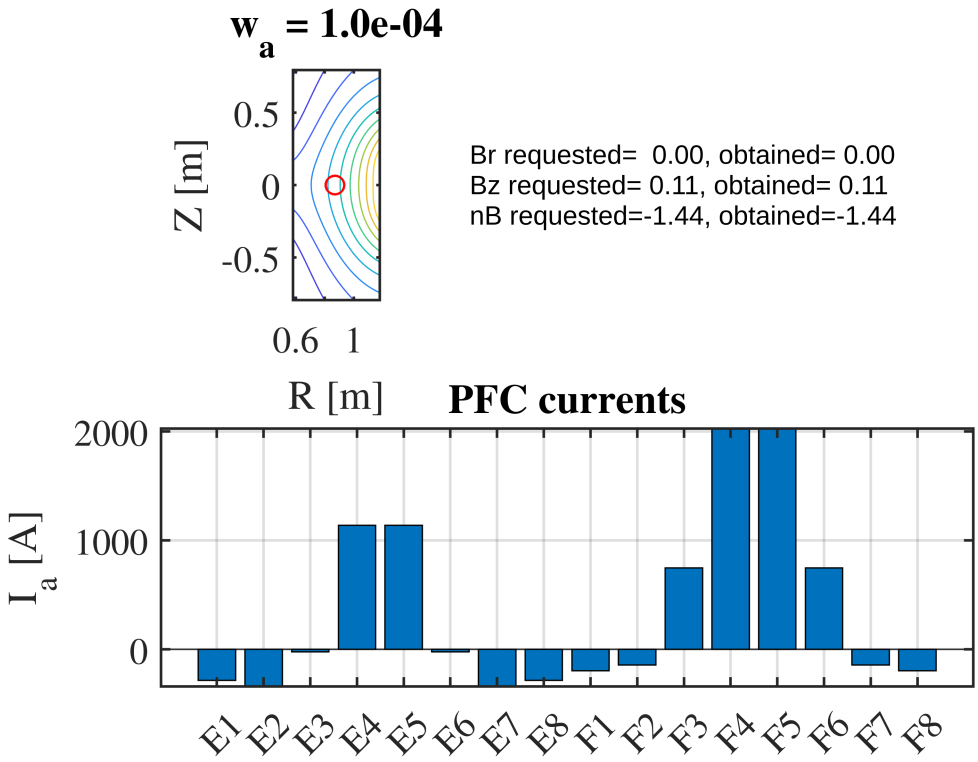
1.b Solve LSQ with fixed contraints

The solution is not influenced by wa. Changing wa will change the minium value of the cost function but not the value of the minimizer. Since the fields are now imposed as constraints, the currents obtained will be high, as in the previous exercise when small wa is used. Set here the current weights and vary them to analyse their impact:

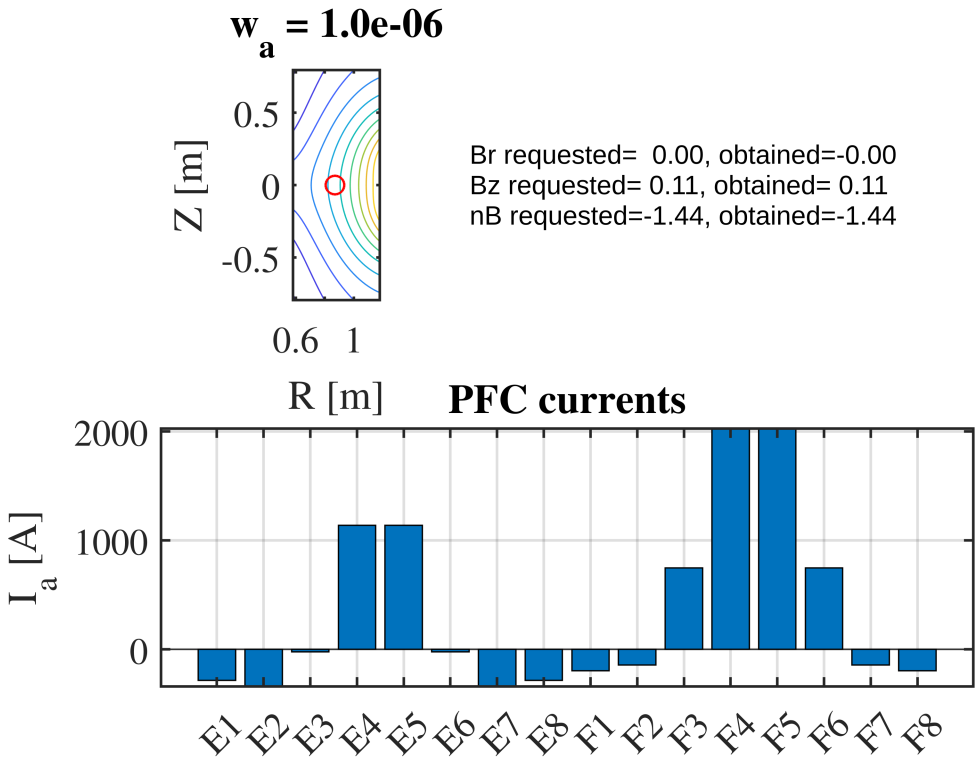
```
wa = [1e-4,1e-6];
```

```
for ii = 1:length(wa)
  % Set up problem with fixed constraints
  Aeq = [Brpa;Bzpa;Cpa];
  beq = [Br0; Bz0; dBz0dr];
  A= wa(ii)*eye(na);
  b = zeros(na,1);

  % Solve using lsqlin Matlab function. This is equivalent of minimizing the
  % functional imposing the constraints with Lagrangian multiplier.
  Ia_fixed = lsqlin(A,b,[],[],Aeq,beq);

  % Obtain magnetic results
  Brq_fixed = Brpa*Ia_fixed;
  Bzq_fixed = Bzpa*Ia_fixed;
  nBq_fixed = -r0 / Bz0*(Cpa*Ia_fixed);

  % Obtain flux, reshape on rz-grid
  psi_fixed = reshape(Mxa* Ia_fixed, [nz,nr]);

  % Plot results:
  fig = figure;
  subplot(2,2,1) % flux map
  contour(rx,zx,psi_fixed); hold on; plot(r0,z0,'ro');
  title(sprintf('w_a = %1.1e',wa(ii)) ), xlabel('R [m]'), ylabel('Z [m]'),
axis equal

  text(1.75, 0, sprintf(' Br requested= %5.2f, obtained=%5.2f \n Bz
requested=%5.2f, obtained=%5.2f \n nB requested=%5.2f, obtained=%5.2f',...
    Br0,Brq_fixed,Bz0,Bzq_fixed,n,nBq_fixed))

  subplot(2,2,[3,4]) % coil currents
  bar(Ia_fixed);
  title('PFC currents'); ylabel('I_a [A]');
  set(gca,'xtick',1:16,'xticklabel',
[num2str((1:8)','E%d');num2str((1:8)','F%d')],'xgrid','on');

  if print_figures
    print_pdf(fig, sprintf('fixed_constraints_wa%1.1e.pdf',wa(ii)));
  end
end
```

```
Minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in
feasible directions, to within the value of the optimality tolerance,
and constraints are satisfied to within the value of the constraint tolerance.

<stopping criteria details>
```




```
Minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in
feasible directions, to within the value of the optimality tolerance,
and constraints are satisfied to within the value of the constraint tolerance.

<stopping criteria details>
```



c. Solve using FBT

```
prefix = 'tcv_102735_fbt';
fileargs = {'pfile',[prefix,'_P'],'gfile',[prefix,'_G'],'xfile',
[prefix,'_X']};
[L,~,LY] = fbt('file',102735,[],'debug',1,fileargs{:});
```

```
 tok    shot    kit      t[s]    Ip[kA]     bp     li  nA     rA[m]     zA[m]    dz[mm]      k       tol  resmaxF res
=============================================================================================================
file 102735      8    0.0100   -400.00  0.19  0.95   1    0.8805   -0.0000   +0.0000  1.62 2.00e-04 1.54e-04
```

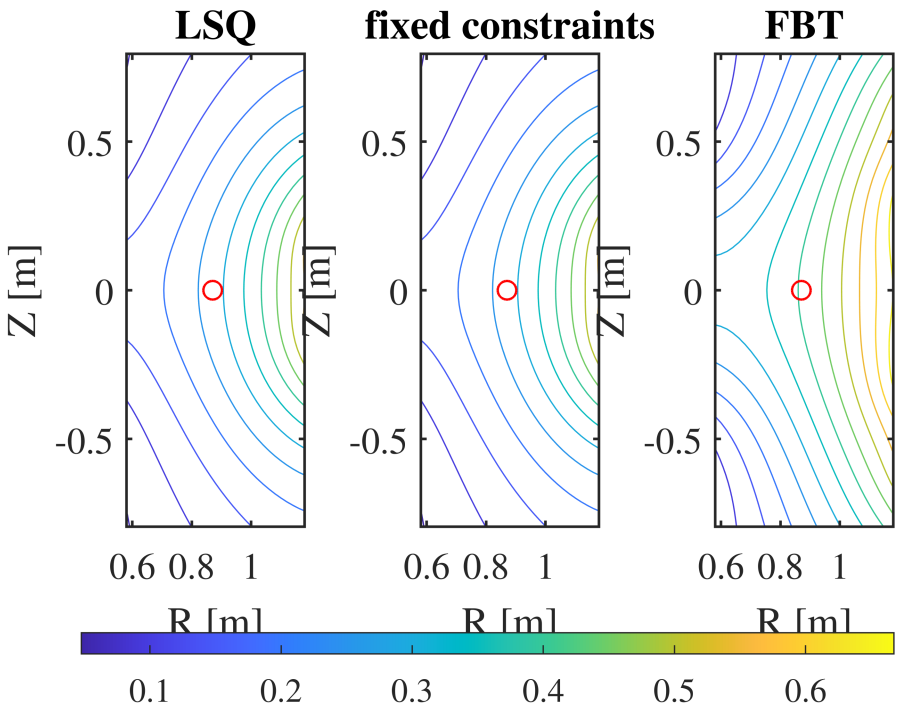
```
% Obtain magnetic field results
Brq_fbt = Brpa*LY.Ia;
Bzq_fbt = Bzpa*LY.Ia;
nBq_fbt = -r0 / Bz0*(Cpa*LY.Ia);

% Obtain flux, reshape on rz-grid
psi_fbt = reshape(Mxa*LY.Ia, [nz,nr]); % reshape on grid
```

Comparison of flux maps obtained by the different methods.

Note, that the field curvatures are similar, but the FBTE field is also designed to yield the desired shape matching in Grad-Shavranof equation, while no such constraint was imposed in the vacuum calculation.

```
% Define minimum and maximum values for colorbar
```

```
cax_max = max([max(psi_fbt(:)),max(psi_fixed(:)),max(psi_lsq(:))]);
cax_min = min([min(psi_fbt(:)),min(psi_fixed(:)),min(psi_lsq(:))]);
psi_grid = -1:0.05:1;
fig = figure;
s_lsq = subplot(1,3,1); % LSQ
contour(s_lsq,rx,zx,psi_lsq, psi_grid); hold on; plot(r0,z0,'ro');
title(s_lsq,'LSQ'), xlabel(s_lsq,'R [m]'), ylabel(s_lsq,'Z [m]'); axis equal
caxis(s_lsq,[cax_min,cax_max]);

s_fixed = subplot(1,3,2); % LSQ with fixed constraints
contour(s_fixed,rx,zx,psi_fixed, psi_grid); hold on; plot(r0,z0,'ro');
title(s_fixed,'fixed constraints'), xlabel(s_fixed,'R [m]'),
ylabel(s_fixed,'Z [m]'); axis equal
caxis(s_fixed,[cax_min,cax_max]);

s_fbt = subplot(1,3,3); % FBTE
contour(s_fbt,rx,zx,psi_fbt,psi_grid); hold on; plot(r0,z0,'ro')
title(s_fbt,'FBT'), xlabel(s_fbt,'R [m]'), ylabel(s_fbt,'Z [m]'); axis equal
caxis(s_fbt,[cax_min,cax_max]);

% Setup colorbar
h = axes(fig,'visible','off'); c = colorbar();
caxis(h,[cax_min,cax_max]);
c.Location = 'southoutside';
c.Position(2) = 0.35*c.Position(2); c.Position(4) = 0.5*c.Position(4);
```

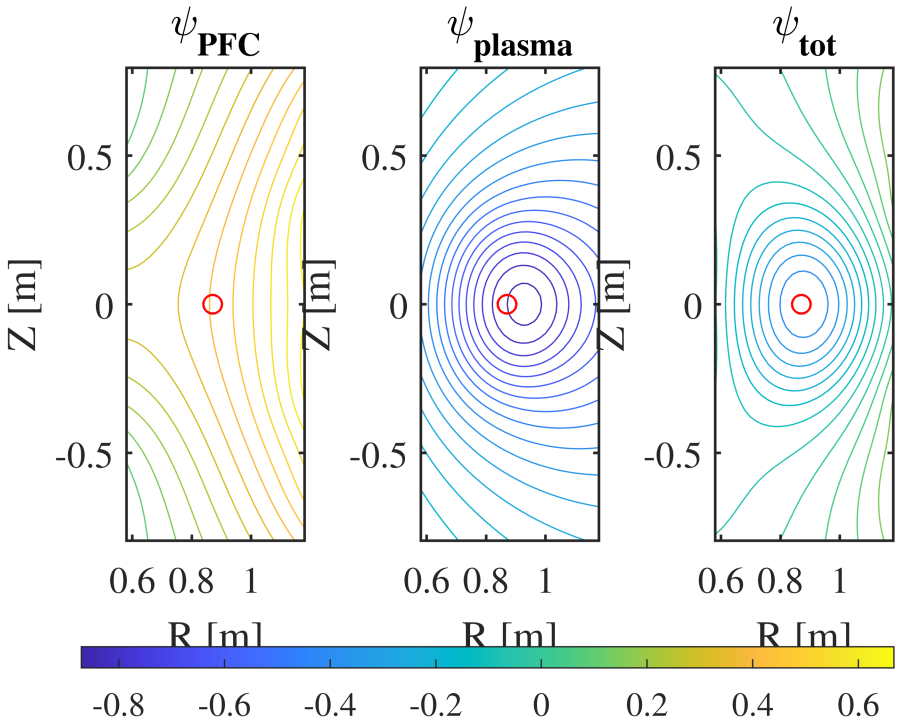


```
if print_figures
  print_pdf(fig,'comparison_1c');
end
```

1.d Compare flux contributions

Comparison of flux obtained using fbt of (i) currents in the PF coils, (ii) plasma current, (iii) total flux. The vacuum poloidal flux actually acts to compress the flux at the low field side of the tokamak, in order to to balance the outward radial force of the plasma.

```
psi_tot = LY.Fx;
psi_coils = reshape(Mxa*LY.Ia, [nz,nr]);
psi_plasma = psi_tot-psi_coils;
psi_grid = -1:0.05:1;
% Define minimum and maximum values for colorbar
cax_max = max([max(psi_tot(:)),max(psi_coils(:)),max(psi_plasma(:))]);
cax_min = min([min(psi_tot(:)),min(psi_coils(:)),min(psi_plasma(:))]);

fig = figure;
s_fbt = subplot(1,3,1); % PFC flux
contour(s_fbt,rx,zx,psi_fbt,psi_grid); hold on; plot(r0,z0,'ro');
title(s_fbt,'\psi_{PFC}'), xlabel(s_fbt,'R [m]'), ylabel(s_fbt,'Z [m]');
axis equal
caxis(s_fbt,[cax_min,cax_max]);

s_pc = subplot(1,3,2); % plasma current induced flux
contour(s_pc,rx,zx,psi_plasma,psi_grid); hold on; plot(r0,z0,'ro'); %
subtract to obtain it
title(s_pc,'\psi_{plasma}'), xlabel(s_pc,'R [m]'), ylabel(s_pc,'Z [m]');
axis equal
caxis(s_pc,[cax_min,cax_max]);

s_tot = subplot(1,3,3); % total flux
contour(s_tot,rx,zx,psi_tot,psi_grid); hold on; plot(r0,z0,'ro');
title(s_tot,'\psi_{tot}'), xlabel(s_tot,'R [m]'), ylabel(s_tot,'Z [m]');
axis equal
caxis(s_tot,[cax_min,cax_max]);

% Setup colorbar
h = axes(fig,'visible','off'); c = colorbar();
caxis(h,[cax_min,cax_max]);
c.Location = 'southoutside';
c.Position(2) = 0.35*c.Position(2); c.Position(4) = 0.5*c.Position(4);
```




```
if print_figures
  print_pdf(fig,'comparison_1d');
end
```

Exercise 2 - FBTE

Effect of power dissipation weight on the coil currents obtained from FBTE. The higher the weight the smaller the current but the worse the agreement of the solution with required LCFS. Look in particar at the bottom leg of the solution.

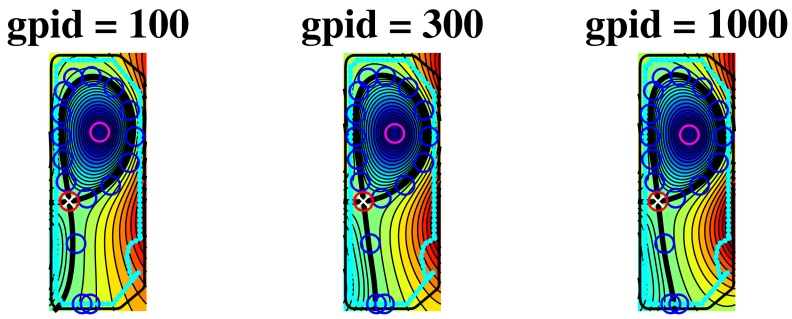
```
gpid = [1e2,3e2,1e3];
exfbte(gpid);
```

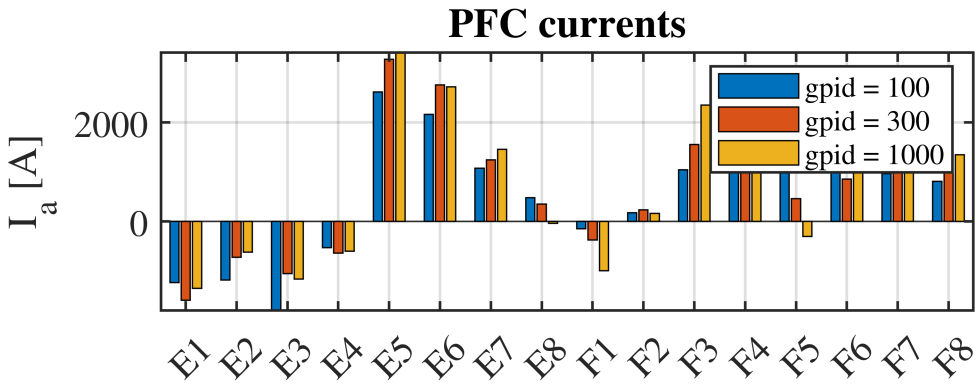
```
FBTX cost function / constraints display
  Tokamak: TCV, shot#102734, t=0.010

Coil current  cost / equality constraints:
E_001              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_002              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_003              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_004              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_005              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_006              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_007              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
E_008              Current:  Ia = +0.00e+00[A]                                  err=1.48e+03[A]
F_001              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_002              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_003              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
```

```
F_004              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_005              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_006              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_007              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]
F_008              Current:  Ia = +0.00e+00[A]                                  err=9.89e+02[A]

Coil current  combination cost / equality constraints:
   none

Dipole  cost / equality constraints:
   none

Coil current limits:
-7.50e+03[A] <=     +1*E_001   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_002   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_003   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_004   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_005   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_006   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_007   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*E_008   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_001   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_002   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_003   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_004   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_005   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_006   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_007   <= +7.50e+03[A]
-7.50e+03[A] <=     +1*F_008   <= +7.50e+03[A]
-1.05e+04[A] <=     +1*F_001    -1*F_002  -0.5*F_003 -0.25*F_004 <= +1.05e+04[A]
-1.05e+04[A] <=   +0.5*F_001    +1*F_002    -1*F_003  -0.5*F_004 -0.25*F_005 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_001  +0.5*F_002    +1*F_003    -1*F_004  -0.5*F_005 -0.25*F_006 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_002  +0.5*F_003    +1*F_004    -1*F_005  -0.5*F_006 -0.25*F_007 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_003  +0.5*F_004    +1*F_005    -1*F_006  -0.5*F_007 -0.25*F_008 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_004  +0.5*F_005    +1*F_006    -1*F_007  -0.5*F_008 <= +1.05e+04[A]
-1.05e+04[A] <=  +0.25*F_005  +0.5*F_006    +1*F_007    -1*F_008 <= +1.05e+04[A]
-4.00e+04[A] <=   +2.1*E_001  +1.1*E_002 +0.67*E_003 +0.21*E_004 -0.21*E_005 -0.67*E_006  -1.1*E_007  -2.1

Passive currents cost / equality constraints:
   none

Coil voltage  cost / equality constraints:
   none

Coil voltage limits:
   none

Magnetic geometry  cost / equality constraints:
r=+0.704 z=-0.120        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=0.00e+00[Wb]
                            Br:  BrSa*Ia + BrSy*Iy = +0                           err=0.00e+00[T]
                            Bz:  BzSa*Ia + BzSy*Iy = +0                           err=0.00e+00[T]
r=+0.730 z=+0.640        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.675 z=+0.560        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.655 z=+0.420        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.655 z=+0.280        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.665 z=+0.140        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.684 z=+0.000        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.704 z=-0.120        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.841 z=+0.650        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.812 z=-0.100        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.978 z=+0.580        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+0.959 z=-0.020        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+1.076 z=+0.440        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
r=+1.076 z=+0.120        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                err=5.00e-03[Wb]
```

```
r=+1.106 z=+0.280        B Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.783 z=-0.750          Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.745 z=-0.380          Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]
r=+0.832 z=-0.750          Psi:   MSa*Ia +  MSy*Iy = +0      +    1*Fb                 err=5.00e-03[Wb]

Plasma profile constraints:
Ip         iD=1 LX.(Ip)(01)=-2.8e+05
qA         iD=1 LX.(qA)(01)=  0.8
fbtlegacy  iD=1
```

tok	shot	kit	t[s]	Ip[kA]	bp	li	nA	rA[m]	zA[m]	dz[mm]	k	tol	resmaxF	res
file	102734	0	0.0100	-280.00	0.00	0.00	1	0.8874	+0.2966	+0.0000	1.86	5.00e-04	NaN	
file	102734	1	0.0100	-280.00	0.81	1.64	1	0.8900	+0.3010	+0.0000	1.77	5.00e-04	2.73e+00	2.6
file	102734	2	0.0100	-280.00	0.49	1.01	1	0.8910	+0.3039	+0.0000	1.77	5.00e-04	4.34e-01	2.8
file	102734	3	0.0100	-280.00	0.49	1.03	1	0.8913	+0.3053	+0.0000	1.77	5.00e-04	1.52e-01	1.0
file	102734	4	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3060	+0.0000	1.77	5.00e-04	5.76e-02	7.1
file	102734	5	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3064	+0.0000	1.77	5.00e-04	2.55e-02	7.1
file	102734	6	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3067	+0.0000	1.77	5.00e-04	1.35e-02	2.1
file	102734	7	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3068	+0.0000	1.77	5.00e-04	8.02e-03	1.4
file	102734	8	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3069	+0.0000	1.77	5.00e-04	5.04e-03	1.6
file	102734	9	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3070	+0.0000	1.77	5.00e-04	3.25e-03	5.3
file	102734	10	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3070	+0.0000	1.77	5.00e-04	2.11e-03	2.3
file	102734	11	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3070	+0.0000	1.77	5.00e-04	1.38e-03	1.4
file	102734	12	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3070	+0.0000	1.77	5.00e-04	9.01e-04	1.0
file	102734	13	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3071	+0.0000	1.77	5.00e-04	5.90e-04	2.1
file	102734	14	0.0100	-280.00	0.49	1.03	1	0.8914	+0.3071	+0.0000	1.77	5.00e-04	3.86e-04	1.6
tok	shot	kit	t[s]	Ip[kA]	bp	li	nA	rA[m]	zA[m]	dz[mm]	k	tol	resmaxF	res
file	102734	0	0.0100	-280.00	0.00	0.00	1	0.8929	+0.2904	+0.0000	1.69	5.00e-04	NaN	
file	102734	1	0.0100	-280.00	0.80	1.66	1	0.8956	+0.2934	+0.0000	1.69	5.00e-04	2.61e+00	1.7
file	102734	2	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2952	+0.0000	1.69	5.00e-04	2.34e-01	2.4
file	102734	3	0.0100	-280.00	0.49	1.04	1	0.8963	+0.2963	+0.0000	1.69	5.00e-04	8.15e-02	1.7
file	102734	4	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2970	+0.0000	1.69	5.00e-04	3.66e-02	2.2
file	102734	5	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2973	+0.0000	1.69	5.00e-04	2.04e-02	1.1
file	102734	6	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2976	+0.0000	1.69	5.00e-04	1.22e-02	1.0
file	102734	7	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2977	+0.0000	1.69	5.00e-04	7.39e-03	1.4
file	102734	8	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2978	+0.0000	1.69	5.00e-04	4.50e-03	1.1
file	102734	9	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2979	+0.0000	1.69	5.00e-04	2.75e-03	3.5
file	102734	10	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2979	+0.0000	1.69	5.00e-04	1.68e-03	2.5
file	102734	11	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2979	+0.0000	1.69	5.00e-04	1.02e-03	3.0
file	102734	12	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2979	+0.0000	1.69	5.00e-04	6.25e-04	1.4
file	102734	13	0.0100	-280.00	0.49	1.04	1	0.8962	+0.2979	+0.0000	1.69	5.00e-04	3.82e-04	2.6
tok	shot	kit	t[s]	Ip[kA]	bp	li	nA	rA[m]	zA[m]	dz[mm]	k	tol	resmaxF	res
file	102734	0	0.0100	-280.00	0.00	0.00	1	0.8940	+0.2834	+0.0000	1.69	5.00e-04	NaN	
file	102734	1	0.0100	-280.00	0.81	1.68	1	0.8971	+0.2864	+0.0000	1.69	5.00e-04	2.60e+00	2.3
file	102734	2	0.0100	-280.00	0.50	1.05	1	0.8978	+0.2883	+0.0000	1.69	5.00e-04	1.83e-01	4.4
file	102734	3	0.0100	-280.00	0.49	1.05	1	0.8979	+0.2896	+0.0000	1.69	5.00e-04	7.60e-02	3.6
file	102734	4	0.0100	-280.00	0.49	1.05	1	0.8978	+0.2904	+0.0000	1.69	5.00e-04	4.02e-02	2.3
file	102734	5	0.0100	-280.00	0.49	1.05	1	0.8978	+0.2908	+0.0000	1.69	5.00e-04	2.38e-02	2.1
file	102734	6	0.0100	-280.00	0.49	1.05	1	0.8978	+0.2911	+0.0000	1.69	5.00e-04	1.44e-02	1.7
file	102734	7	0.0100	-280.00	0.49	1.05	1	0.8978	+0.2913	+0.0000	1.69	5.00e-04	8.71e-03	1.7
file	102734	8	0.0100	-280.00	0.49	1.05	1	0.8978	+0.2914	+0.0000	1.69	5.00e-04	5.28e-03	1.0
file	102734	9	0.0100	-280.00	0.49	1.05	1	0.8978	+0.2915	+0.0000	1.69	5.00e-04	3.20e-03	1.3
file	102734	10	0.0100	-280.00	0.49	1.05	1	0.8977	+0.2915	+0.0000	1.69	5.00e-04	1.94e-03	2.1
file	102734	11	0.0100	-280.00	0.49	1.05	1	0.8977	+0.2915	+0.0000	1.69	5.00e-04	1.18e-03	4.0
file	102734	12	0.0100	-280.00	0.49	1.05	1	0.8977	+0.2916	+0.0000	1.69	5.00e-04	7.14e-04	1.8
file	102734	13	0.0100	-280.00	0.49	1.05	1	0.8977	+0.2916	+0.0000	1.69	5.00e-04	4.33e-04	7.7






```
if print_figures
  print_pdf(gcf,'fbte_gpid.pdf');
end
```

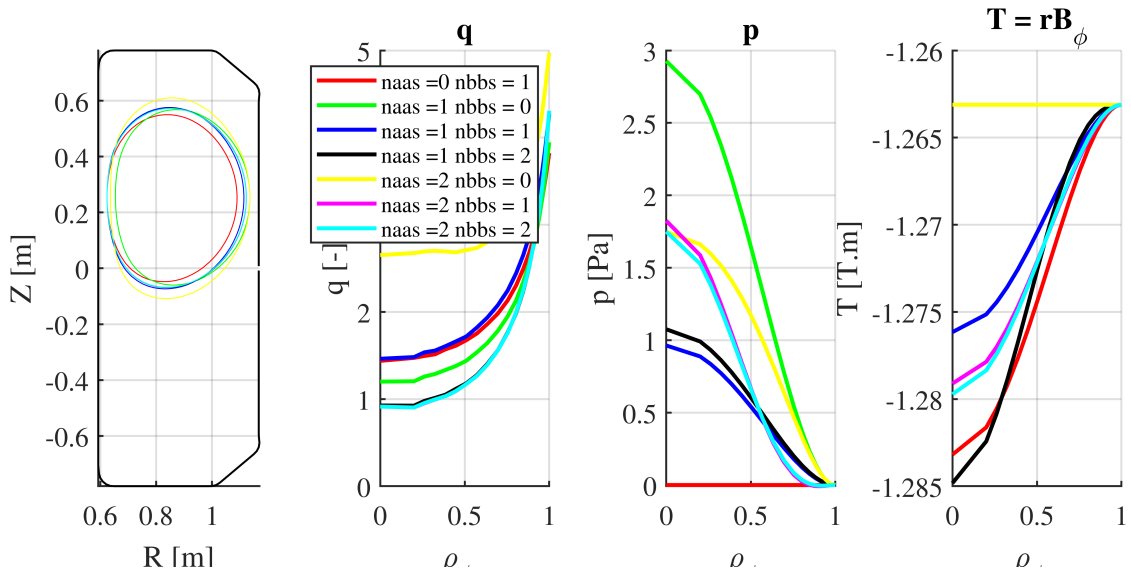
Exercise 3 - LIUQE Reconstruction

Study of the effect of the basis functions naas and nbbs to parametrize p' and TT' in the Grad-Shafranov equation. We see, that the equilibrium reconstruction is very sensitive to the choice of the basis functions used. To study this, we can use here the function exliuqe that scans for naas & nbbs between 0 and 2.

Limited configuration

```
shot = 40000;
time = 0.1;
exliuqe(shot, time);
```

```
Warning: TCV#40000 0.1000s/0: number of found domains (2) exceeds maximum number (1)
Warning: TCV#40000 0.1000s/26: fgeF call failed for t=0.100000
Warning: TCV#40000 0.1000s/0: number of found domains (2) exceeds maximum number (1)
Warning: TCV#40000 0.1000s/50: meqpostq contour finding using rtcimex did not converge
Warning: TCV#40000 0.1000s/50: No convergence after 50 iterations - freezing plasma domain
Warning: TCV#40000 0.1000s/50: No convergence after 50 iterations - freezing plasma domain
Warning: TCV#40000 0.1000s/50: No convergence after 50 iterations - freezing plasma domain
```

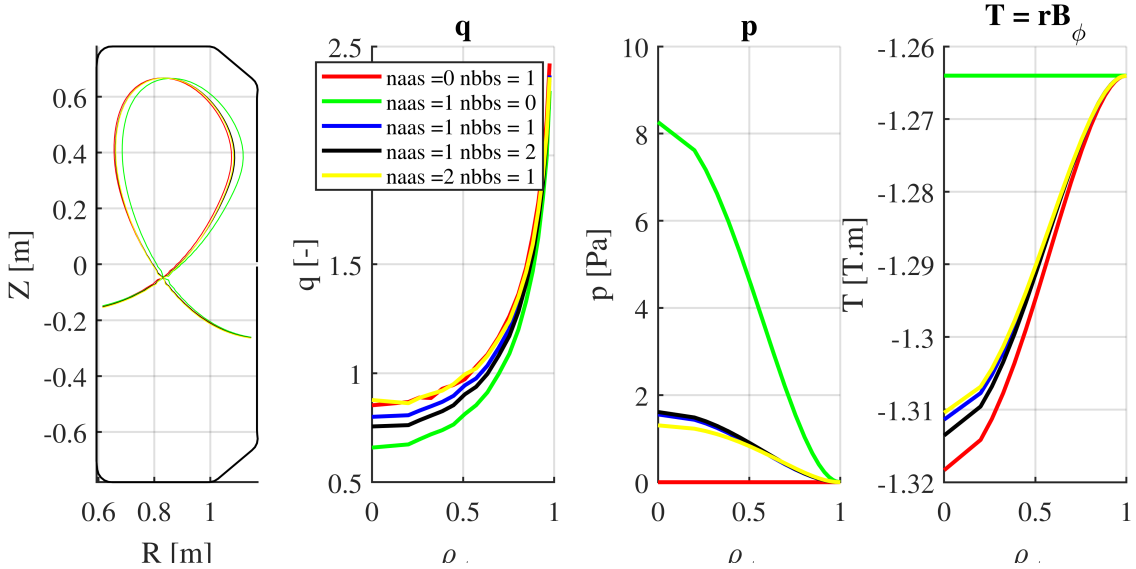



```
if print_figures
  print_pdf(gcf,'liuqe_limited');
end
```

Diverted configuration

```
shot = 40000;
time = 0.3;
exliuqe(shot, time);
```

```
Warning: TCV#40000 0.3000s/50: No convergence after 50 iterations - freezing plasma domain
Warning: TCV#40000 0.3000s/100: iterations exceeded
Warning: TCV#40000 0.3000s/50: No convergence after 50 iterations - freezing plasma domain
Warning: TCV#40000 0.3000s/100: iterations exceeded
Warning: TCV#40000 0.3000s/50: No convergence after 50 iterations - freezing plasma domain
```




```
Warning: TCV#40000 0.3000s/0: number of found domains (4) exceeds maximum number (1)
Warning: TCV#40000 0.3000s/8: fgeF call failed for t=0.300000
```

```
Warning: TCV#40000 0.3000s/0: number of found domains (4) exceeds maximum number (1)
Warning: TCV#40000 0.3000s/50: meqpostq contour finding using rtcimex did not converge
```

```
if print_figures
  print_pdf(gcf,'liuqe_diverted');
end
```

Additional functions for figure plots and pdf save

```
function print_pdf(fig, name)
set(fig,'Units','Inches'); pos = get(fig,'Position');
set(fig,'PaperPositionMode','Auto','PaperUnits','Inches','PaperSize',
[pos(3), pos(4)])
print(fig,name,'-dpdf','-r0');
end
```