Control and operations of tokamaks
Exercise Session 8 - Plasma 1D profile evolution
Solutions

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SOLUTION 1

We investigate 3 I_p ramp-ups. The first one stops at t=20s and the last one at t=100s, all reaching the same value at the flat-top. We also want the density to ramp-up at the same time as I_p. This is what happens in practice in experiment[1]. The simple way is to keep the same spatial distribution of the density, and make its amplitude evolve in time. We thus generate the time evolution inside `ne0`, ramping from 0 to its maximum, at the same time as I_p does. Note that the final density, `negauss` is obtained by multiplying the basis functions by the initial basis factors stored in `V`, therefore doing:

$$n_e(\rho, 0) = \sum_{\alpha=1}^{n} \Lambda_\alpha(\rho)\hat{n}_{e,\alpha}(0) \quad (1)$$

Then, we multiply this initial profile to the time evolution:

$$n_e(\rho, t) = \underbrace{\left[n_e(\rho_1, 0) \quad ... \quad n_e(\rho_N, 0)\right]}_{\text{space}\times 1} * \underbrace{\left[0 \quad ... \quad 1\right]}_{1\times\text{time}} \quad (2)$$

Then you do the inverse operation of equation 1 to obtain the new basis factors in `V`.

```
tflattopgrid = 20:40:100;
cgrid = {'b','r','k','m'};
clear out simres
for ii=1:numel(tflattopgrid)
    tflattop = tflattopgrid(ii);
    U(1,:) = rampfun(params.tgrid,0,4e6,tflattop,12e6); % input Ip trace

```

[1] it can be explained by three facts: the confinement of the density increases with I_p, we do not want to exceed the Greenwald limit and break-down must happen at low density so this means you must have to ramp-up

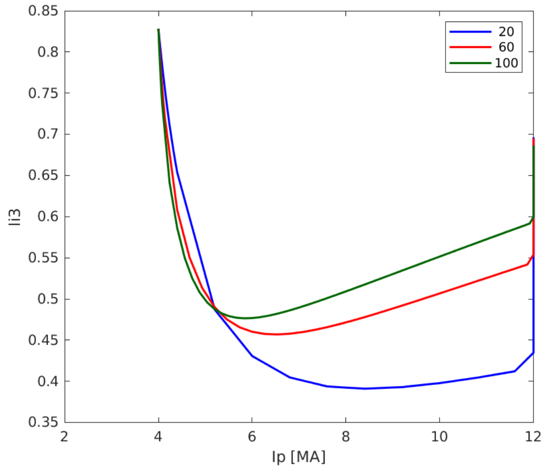
```
    negauss = model.ne.Lamgauss*V(model.ne.vind,1);
    ne0 = rampfun(params.tgrid,0,1,tflattop,5);
    negauss_varying = negauss*ne0;
    V(model.ne.vind,:) = model.ne.Lamgauss \ negauss_varying;
    V(model.ni.vind,:) = 0.9*V(model.ne.vind,:);

    simres{ii} = RAPTOR_predictive(x0,g,V,U,model,params); % run sim
    out{ii} = RAPTOR_out(simres{ii},model,params); % get outputs
end

RAPTOR_plot_GUI(out)
```

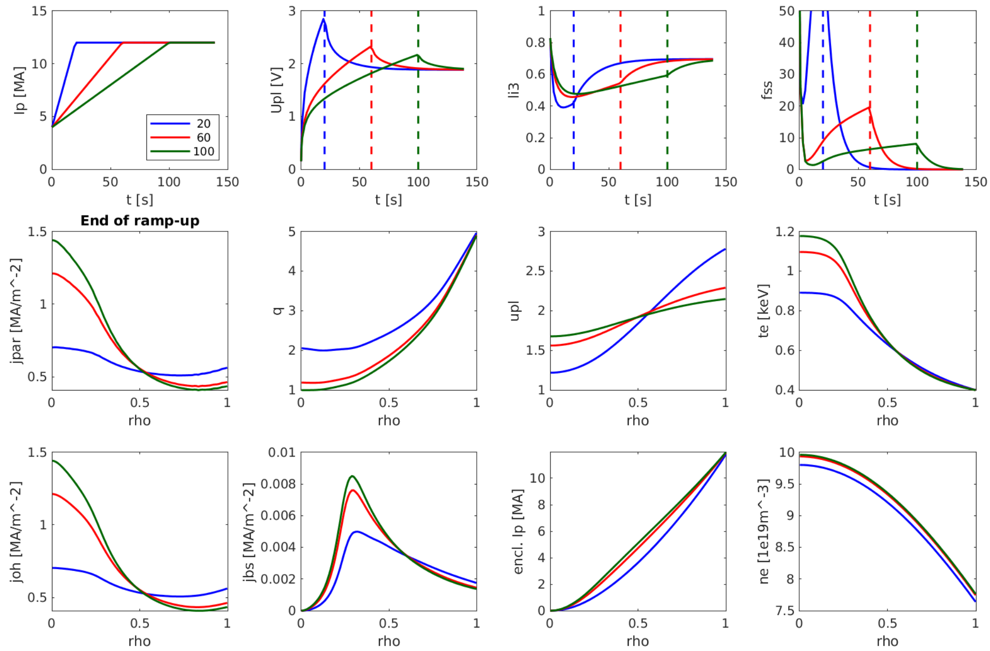
The fastest ramp rate leads to a non-monotonic current density profile and flatter, or more reversed, q profiles. This can lead to transport barriers. In reality, the ramp rate is limited by MHD modes which can appear, especially for very steep current density profiles. Let us plot the time evolution of some global quantities and a set of profiles at the end of ramp-up note:

- a faster ramp-up rate leads to a lower value of the internal inductance throughout the entire ramp-up phase (consider the comparison in the (I_p,$l_{i,3}$)-plane), corresponding to a broader j_{par} profile
- the quantity `out.f_ss` is a metric for the relaxation of the current diffusion, defined as

  ```
  f_ss = sum(out.dupldrho.^2)
  ```

  (remember: j_{par} is fully diffused when dupldrho zero ; note: by applying a slower ramp-up the current profile is more stationary by the beginning of flat-top)
- the faster ramp-up requires larger values of the applied loop voltage





The fastest ramp rate leads to a non-monotonic current density profile and flatter, or more reversed, q profiles. This can lead to transport barriers. In reality, the ramp rate is limited by MHD modes which can appear, especially for very steep current density profiles. If you follow the evolution of `out.upl` in time during the flat-top, you should see that it becomes flatter and flatter with time. Our profiles tends to be stationnary!

SOLUTION 2

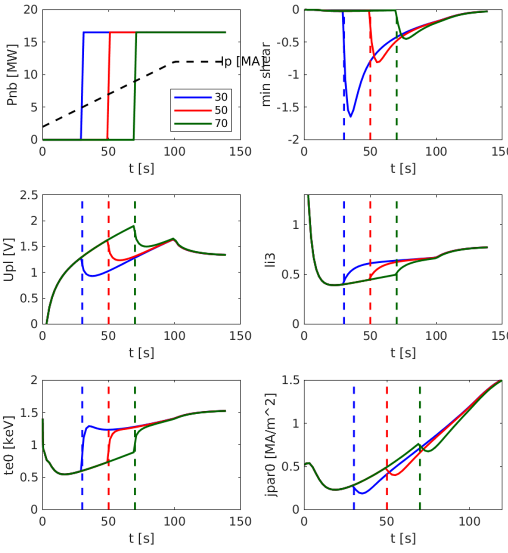
Now let's add some external heating & current drive system (HCD). We propose to study the effect of the NBI starting time on the current density and kinetic profiles, as well as the impact of reversed-shear on the onset of an ITB.

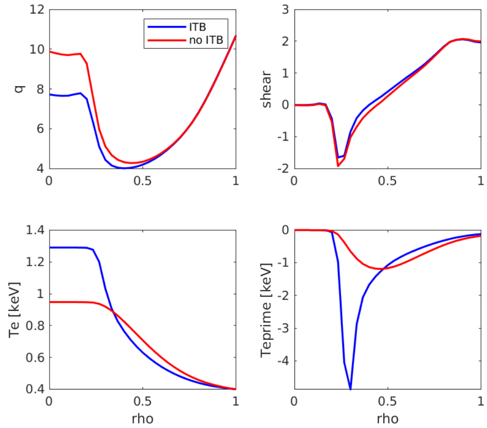
```
clear simres out
% Back to default Ip trace
tFT = 100;
U(1,:) = rampfun(params.tgrid,0,2e6,tFT,12e6); % input Ip trace
tstartgrid = [30 50 70];
for ii=1:numel(tstartgrid)
    tstart = tstartgrid(ii);
    U(model.nbhcd.uind(model.nbhcd.ind_power),:) = 0;
    U(model.nbhcd.uind(model.nbhcd.ind_power),params.tgrid>tstart) = 16.5e6
    ;
    U(model.echcd.uind(model.echcd.ind_power),:) = 0;
    simres{ii} = RAPTOR_predictive(x0,g,V,U,model,params);
    out{ii} = RAPTOR_out(simres{ii},model,params);
    % we can run a second set of simulations, turning of the reduction of
    % diffusion due to negative magnetic shear
    params_noITB = params;
    params_noITB.chi_e.aitb = 0;
    simres_noITB{ii} = RAPTOR_predictive(x0,g,V,U,model,params_noITB);
    out_noITB{ii} = RAPTOR_out(simres_noITB{ii},model,params_noITB);
 end
RAPTOR_plot_GUI(out);
```

Let us plot some global time traces starting the NBI heating leads to a rise in electron temperature (Te0) slowing down current diffusion note that starting the NBI heating leads to:

- slower rise of the central current density (jpar0)
- reduction of the edge loop voltage (higher signeo)
- negative shear

Comparing the curves on the right graph, we indeed see that, in the case where `chi_e.aitb = 1` (blue curve), there is a negative shear leading to a steeper radial gradient of T_e.





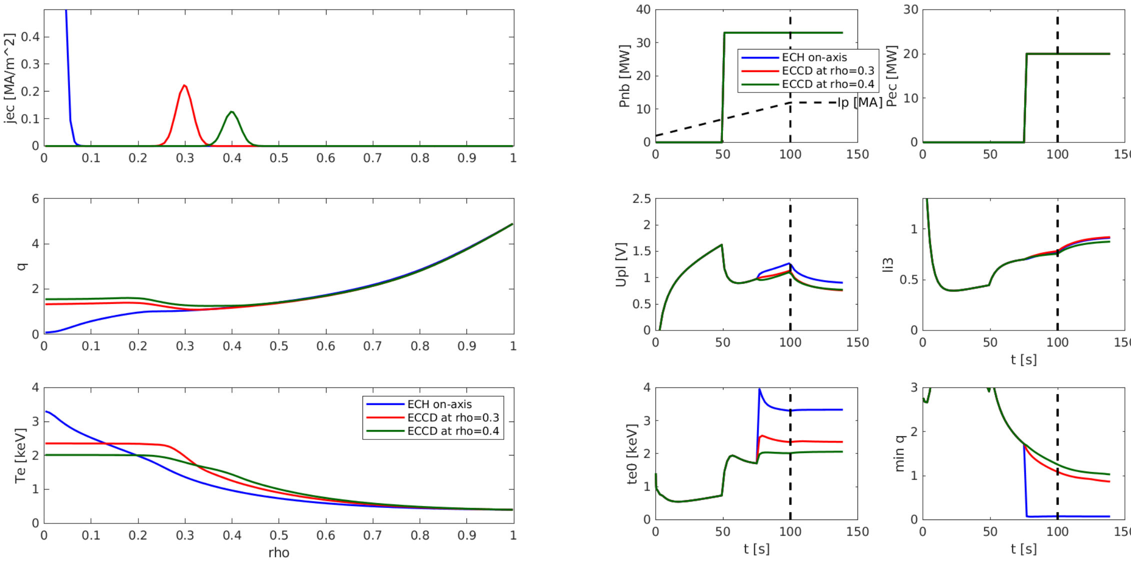
Turning on the heating very early slows the current penetration, but is not enough to create a transport barrier.

SOLUTION 3

Now let's turn on the ECCD! On this question we try to obtain an ITB by tailoring the q profile.

```
clear simres out
tFT = 100;
U(1,:) = rampfun(params.tgrid,0,2e6,tFT,12e6); % input Ip trace
U(model.nbhcd.uind(model.nbhcd.ind_power),:) = 0;
U(model.nbhcd.uind(model.nbhcd.ind_power),params.tgrid>50) = 33e6; % early NBI

tstart = 75;
for ii=1:3
    U(model.echcd.uind(model.echcd.ind_power(1:3)),:) = 0; % ECCD
    U(model.echcd.uind(model.echcd.ind_power(ii)),params.tgrid>tstart) = 20e6; % ECCD
    simres{ii} = RAPTOR_predictive(x0,g,V,U,model,params);
    out{ii} = RAPTOR_out(simres{ii},model,params);
end
hf = RAPTOR_plot_GUI(out);
```

Resulting simulations for cases (a), (b) and (c) are presented below. Adding off-axis ECCD at $\rho = 0.4$ gives (at least transiently) a reverse-shear q profile and thus triggers a transport barrier, as is visible from the locally very steep temperature gradient on the T_e blue curve. When looking at the parallel resistivity $\sigma_{\parallel}$, you can see that when the blue curve start to have a higher temperature, it also starts to have a higher resistivity.



SOLUTION 4

We leave you to explore this question. Adding early ECCD and early NBI should trigger a reverse-shear q-profile while keeping the minimum of q above 1 for a certain time.

SOLUTION 5

```
fprintf('simres.X has size %d x %d\n',size(simres{1}.X,1),size(simres{1}.X,2));
% second dimension corresponds to time, first dimension is: 2 x nsp
% 32 spline coefficients for psi, 32 spline coefficients for Te
% each can be accessible through the x indices stored in model

psi_hat = simres{1}.X(model.psi.xind,:);
te_hat = simres{1}.X(model.te.xind,:);

% let's reconstruct psi and te profiles for t = 100s
it = 64;
psi_profile = model.psi.Lam*psi_hat;
te_profile = model.te.Lam*te_hat;
psi_profile_gauss = model.psi.Lamgauss*psi_hat;
te_profile_gauss = model.te.Lamgauss*te_hat;

% Compare results on sparse grid
figure('Position',[163 189 1060 594]);
subplot(121);plot(model.rgrid.rho,psi_profile(:,it),'Linewidth',2);hold on;plot(out{1}.rho,out{1}.psi(:,it),'--','Linewidth',2);title('\psi');legend('your \psi','\psi from out');xlabel('\rho');
subplot(122);plot(model.rgrid.rho,te_profile(:,it),'Linewidth',2);hold on;plot(out{1}.rho,out{1}.te(:,it),'--','Linewidth',2);title('T_e');legend('your T_e','T_e from out');xlabel('\rho');
suptitle(sprintf('t=%.2fs',params.tgrid(it)));

% Compare results on Gauss grid
figure('Position',[163 189 1060 594]);
subplot(121);plot(model.rgrid.rhogauss,psi_profile_gauss(:,it),'Linewidth',2);hold on;plot(out{1}.rhogauss,out{1}.psigauss(:,it),'--','Linewidth',2);title('\psi');legend('your \psi','\psi from out');xlabel('\rho_{gauss}');
subplot(122);plot(model.rgrid.rhogauss,te_profile_gauss(:,it),'Linewidth',2);hold on;plot(out{1}.rhogauss,out{1}.tegauss(:,it),'--','Linewidth',2);title('T_e');legend('your T_e','T_e from out');xlabel('\rho_{gauss}');
suptitle(sprintf('t=%.2fs',params.tgrid(it)));

% Compare rho and rhogauss profiles
figure('Position',[163 189 1060 594]);
subplot(121);plot(model.rgrid.rho,psi_profile(:,it),'*','Linewidth',2);yyaxis right;plot(model.rgrid.rho,te_profile(:,it),'o','Linewidth',2);legend('your \psi','your T_e');xlabel('\rho');title('On sparse grid');
subplot(122);plot(model.rgrid.rhogauss,psi_profile_gauss(:,it),'*','Linewidth',2);yyaxis right;plot(model.rgrid.rhogauss,te_profile_gauss(:,it),'o','Linewidth',2);legend('your \psi','your T_e');xlabel('\rho_{gauss}');title('On gauss grid');
suptitle(sprintf('t=%.2fs',params.tgrid(it)));
```