Examples of elementary plasma instabilities in BOUT++

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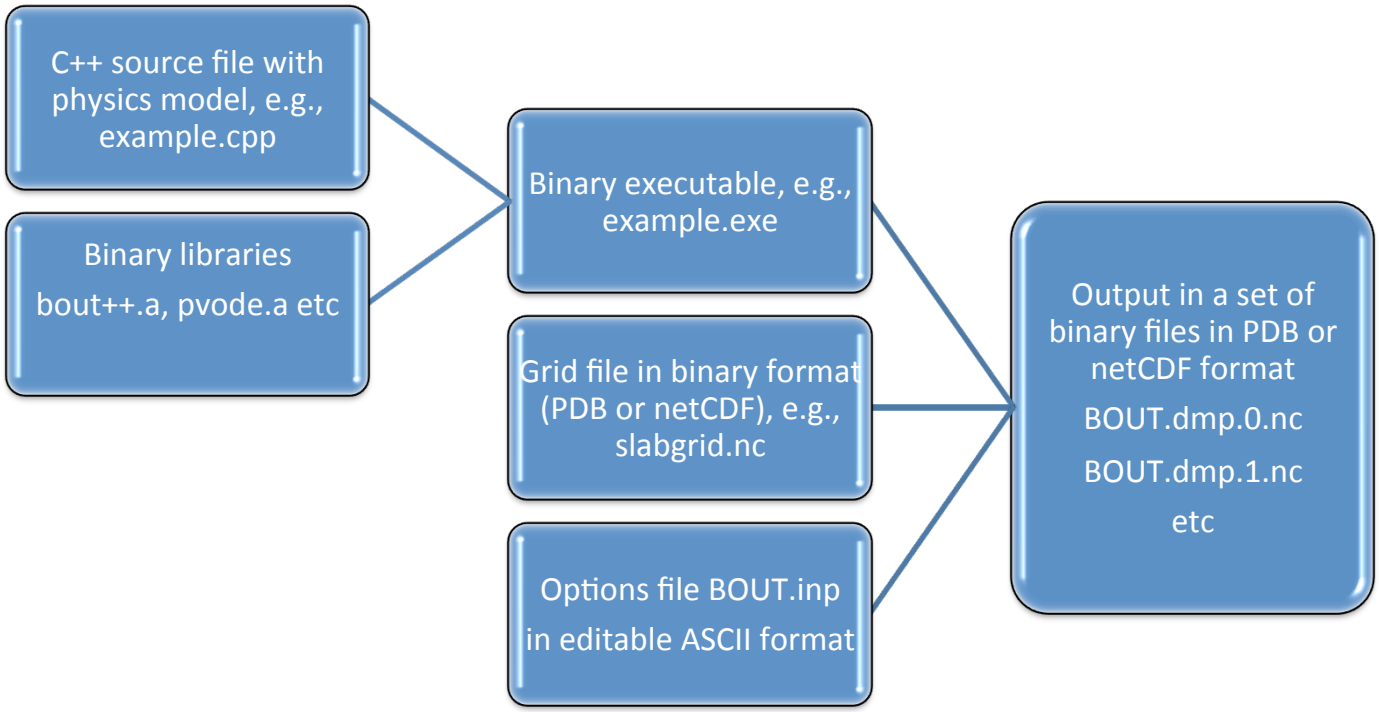
Test problems are essential for verification, also helpful for new users learning the code

- Test problems initially used for debugging and verification testing
- Provide simple fast demonstrations how to use the code
- Can promptly point to bugs introduced in the code
- Suite of test problems is a part of code distribution, including
  - Gravitational interchange instability
  - Resistive drift instability
  - Shear-Alfven wave
  - Resistive and ideal ballooning
  - Axisymmetric problem (benchmarked against UEDGE)
  - Neutral hydrodynamics (benchmarked against ICF hydro code)
  - More examples still being added

- Most of these tests can be run automatically by scripts

Several steps are involved in setting up and running example cases in BOUT++



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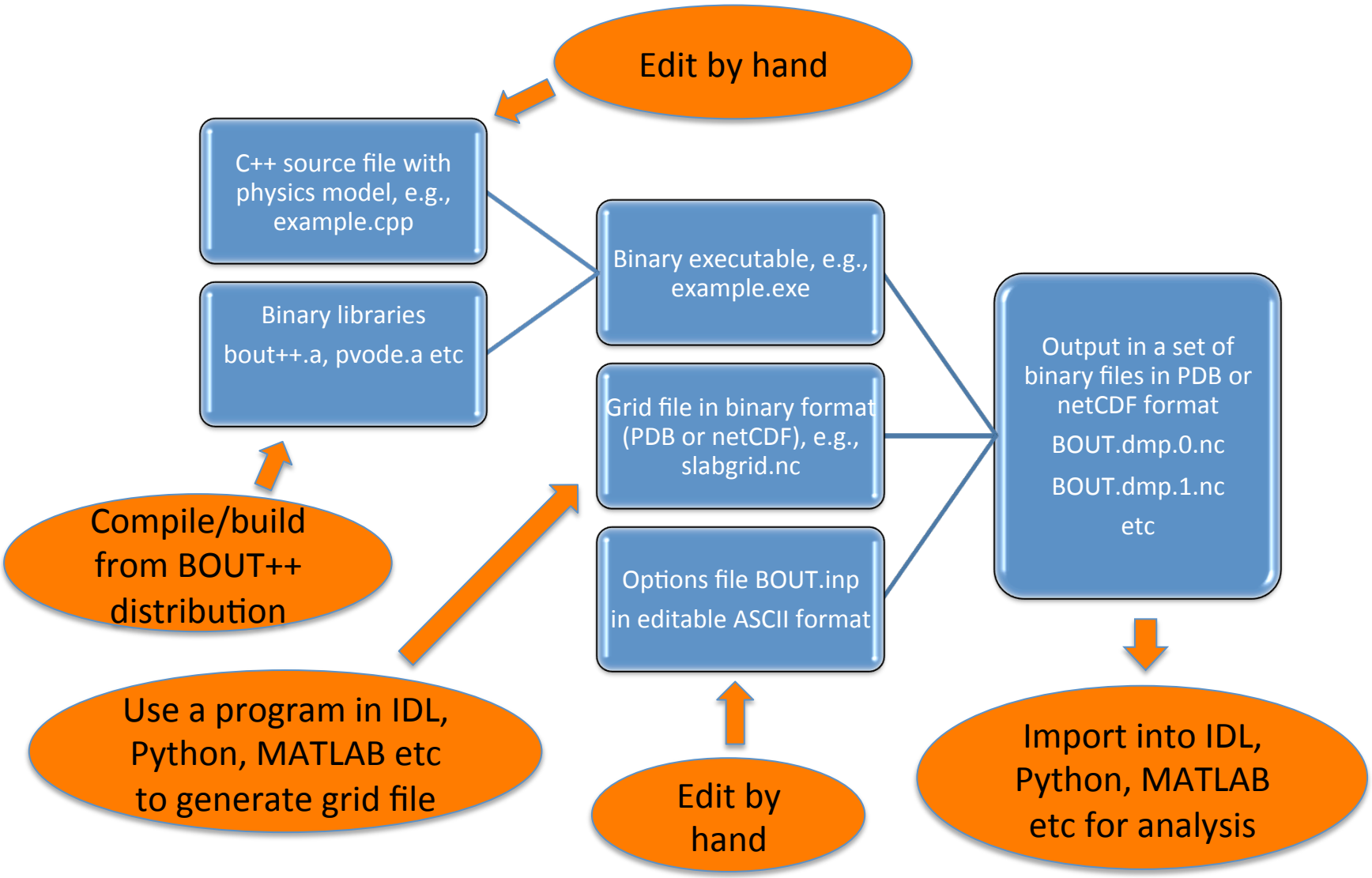
Several steps are involved in setting up and running example cases in BOUT++



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Physics model for gravitational flute instability

From "*Plasma physics and controlled fusion*" by F. F. Chen

To find the growth rate, we can perform the usual linearized wave analysis for waves propagating in the y direction: $\mathbf{k} = k\hat{\mathbf{y}}$. The perturbed ion equation of motion is

$$M(n_0 + n_1)\left[\frac{\partial}{\partial t}(\mathbf{v}_0 + \mathbf{v}_1) + (\mathbf{v}_0 + \mathbf{v}_1)\cdot\nabla(\mathbf{v}_0 + \mathbf{v}_1)\right]$$
$$= e(n_0 + n_1)[\mathbf{E}_1 + (\mathbf{v}_0 + \mathbf{v}_1)\times\mathbf{B}_0] + M(n_0 + n_1)\mathbf{g} \qquad [6\text{-}38]$$

We now multiply Eq. [6-36] by $1 + (n_1/n_0)$ to obtain

$$M(n_0 + n_1)(\mathbf{v}_0\cdot\nabla)\mathbf{v}_0 = e(n_0 + n_1)\mathbf{v}_0\times\mathbf{B}_0 + M(n_0 + n_1)\mathbf{g} \qquad [6\text{-}39]$$

Subtracting this from Eq. [6-38] and neglecting second-order terms, we have

$$Mn_0\left[\frac{\partial\mathbf{v}_1}{\partial t} + (\mathbf{v}_0\cdot\nabla)\mathbf{v}_1\right] = en_0(\mathbf{E}_1 + \mathbf{v}_1\times\mathbf{B}_0) \qquad [6\text{-}40]$$

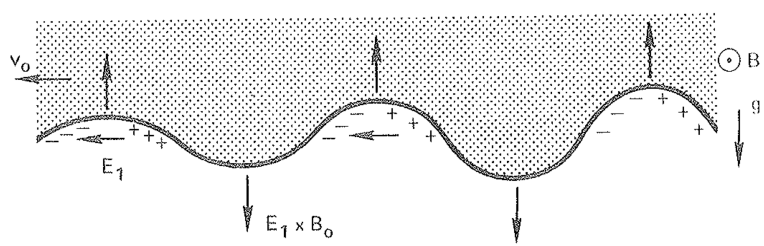

FIGURE 6-11 Physical mechanism of the gravitational instability.

Physics equations in BOUT

$$\frac{\partial\tilde{\varpi}}{\partial t} = 2\omega_{ci} b_0 \times \kappa \bullet \nabla\tilde{P}$$

$$\frac{\partial\tilde{N}_i}{\partial t} = -\tilde{V}_E \bullet \nabla N_{i0}$$

$$\tilde{\varpi} \equiv N_{i0}\nabla_\perp^2\tilde{\phi}$$

$$\tilde{P} = T_0\tilde{N}_i$$

- **Equations for perturbations**
- **Assumed equilibrium terms are in balance**
- **Vorticity equation combines current continuity and perpendicular momentum**
- **Certain ordering assumptions built in**

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In the C++ physics model source file equations are encoded in readable form

In examples/interchange-instability/2fluid.cxx

Setting up physics model in the code

$$\frac{\partial \tilde{N}_i}{\partial t} = -\tilde{V}_E \bullet \nabla N_{i0}$$

```
File  Edit  Options  Buffers  Tools  C++  Help

    // Set boundary condition on jpar
    jpar.applyBoundary();

    // Need to communicate jpar
    mesh->communicate(jpar);

    Ve = Vi - jpar/Ni0;
    Ajpar = Ve;
  }else {

    Ve = Ajpar + Apar;
    jpar = Ni0*(Vi - Ve);
  }

  // DENSITY EQUATION

  ddt(Ni) = 0.0;
  if(evolve_ni) {
    ddt(Ni) -= vE_Grad(Ni0, phi);

    /*
      ddt(Ni) -= vE_Grad(Ni, phi0) + vE_Grad(Ni0, phi) + vE_Grad(Ni, phi);
      ddt(Ni) -= Vpar_Grad_par(Vi, Ni0) + Vpar_Grad_par(Vi0, Ni) + Vpar_Grad_par(Vi, Ni);
      ddt(Ni) -= Ni0*Div_par(Vi) + Ni*Div_par(Vi0) + Ni*Div_par(Vi);
      ddt(Ni) += Div_par(jpar);
      ddt(Ni) += 2.0*V_dot_Grad(b0xcv, pe);
      ddt(Ni) -= 2.0*(Ni0*V_dot_Grad(b0xcv, phi) + Ni*V_dot_Grad(b0xcv, phi0) + Ni*V_dot_Grad(b0xcv, phi));
    */
  }
```

Also, in same source file

$$\tilde{\varpi} \equiv N_{i0} \nabla_\perp^2 \tilde{\phi}$$

$$\tilde{P} = T_0 \tilde{N}_i$$

$$\frac{\partial \tilde{\varpi}}{\partial t} = 2\omega_{ci} b_0 \times \kappa \bullet \nabla \tilde{P}$$

```
File  Edit  Options  Buffers  Tools  C++  Help

  // ELECTRON TEMPERATURE

  ddt(Te) = 0.0;
  if(evolve_te) {
    ddt(Te) -= vE_Grad(Te0, phi) + vE_Grad(Te, phi0) + vE_Grad(Te, phi);
    ddt(Te) -= Vpar_Grad_par(Ve, Te0) + Vpar_Grad_par(Ve0, Te) + Vpar_Grad_par(Ve, Te);
    ddt(Te) += 1.333*Te0*( V_dot_Grad(b0xcv, pe)/Ni0 - V_dot_Grad(b0xcv, phi) );
    ddt(Te) += 3.333*Te0*V_dot_Grad(b0xcv, Te);
    ddt(Te) += (0.6666667/Ni0)*Div_par_K_Grad_par(kapa_Te, Te);
  }

  // ION TEMPERATURE

  ddt(Ti) = 0.0;
  if(evolve_ti) {
    ddt(Ti) -= vE_Grad(Ti0, phi) + vE_Grad(Ti, phi0) + vE_Grad(Ti, phi);
    ddt(Ti) -= Vpar_Grad_par(Vi, Ti0) + Vpar_Grad_par(Vi0, Ti) + Vpar_Grad_par(Vi, Ti);
    ddt(Ti) += 1.333*( Ti0*V_dot_Grad(b0xcv, pe)/Ni0 - Ti*V_dot_Grad(b0xcv, phi) );
    ddt(Ti) -= 3.333*Ti0*V_dot_Grad(b0xcv, Ti);
    ddt(Ti) += (0.6666667/Ni0)*Div_par_K_Grad_par(kapa_Ti, Ti);
  }

  // VORTICITY

  ddt(rho) = 0.0;
  if(evolve_rho) {
    /*
    ddt(rho) -= vE_Grad(rho0, phi) + vE_Grad(rho, phi0) + vE_Grad(rho, phi);
    ddt(rho) -= Vpar_Grad_par(Vi, rho0) + Vpar_Grad_par(Vi0, rho) + Vpar_Grad_par(Vi, rho);
    */

    //ddt(rho) += 2.0*Bxy*V_dot_Grad(b0xcv, pei);
    ddt(rho) += 2.0*mesh->Bxy*b0xcv*Grad(pei);

    //ddt(rho) += Bxy*Bxy*Div_par(jpar, CELL_CENTRE);
  }
```


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Grid file can be generated with an IDL routine

Generating arrays of geometry and plasma parameters and saving them In binary file

In BOUT-1.0/tools/slab/slab.pro

File Edit Options Buffers Tools Debug IDLWAVE Help

```
; Slab geometry grid generator
;
; Optional keywords:
; =================
;
; output   =   Set output file name
; thin     =   Use thin radial box approximation
;               so Bpxy = constant, but gradient is non-zero
;
; ni  = Ion density in 10^20 m^-3
; Ti  = ion temperature in eV
; Te  = electron temperature in eV
;
; Rmaj     = Major radius [meters]
; rminor   = Minor radius [m]
; dr       = Radial width of box [m]
; r_wid    = Radial extent, normalised to gyro-radius r_wid = dr / rho_i
;
; q        = Safety factor q = r*Bt/(R*Bp) at middle of box
; dq       = Change in q. Will go from q-dq/2 to q+dq/2
;
; L_T      = Temperature length scale [m]
; L_n      = Density length scale [m]
; eta_i    = Ratio of density to temp. length scales eta = L_n / L_T

PRO slab, output=output, thin=thin, nx=nx, ny=ny, $
          ni=ni, Ti=Ti, Te=Te, $
          Rmaj=Rmaj, rminor=rminor, dr=dr, $
          r_wid=r_wid, $
          q=q, dq=dq, $
          L_T=L_T, L_n=L_n, eta_i=eta_i

  if not keyword_set(NX) then nx = 68 ; Radial grid points
  if not keyword_set(NX) then ny = 32 ; Poloidal (parallel) grid points
```

File Edit Options Buffers Tools Debug IDLWAVE Help

```
  yup_xout = [-1]
  ydown_xin = [0]
  ydown_xout = [-1]
  nrad = [nx]
  npol = [ny]

  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

  PRINT, "Writing grid to file "+output

  handle = file_open(output, /CREATE)
  ; Size of the grid

  s = file_write(handle, "nx", nx)
  s = file_write(handle, "ny", ny)

  ; Topology for original scheme
  s = file_write(handle, "ixseps1", ixseps1)
  s = file_write(handle, "ixseps2", ixseps2)
  s = file_write(handle, "jyseps1_1", jyseps1_1)
  s = file_write(handle, "jyseps1_2", jyseps1_2)
  s = file_write(handle, "jyseps2_1", jyseps2_1)
  s = file_write(handle, "jyseps2_2", jyseps2_2)
  s = file_write(handle, "ny_inner", ny_inner);

  ; Grid spacing

  s = file_write(handle, "dx", dx)
  s = file_write(handle, "dy", dy)

  s = file_write(handle, "ShiftAngle", ShiftAngle)
  s = file_write(handle, "zShift", zShift)
;  s = file_write(handle, "pol_angle", pol_angle)
;  s = file_write(handle, "ShiftTorsion", dqdpsi)
--:-- slab.pro        (IDLWAVE Abbrev Fill)--L239--70%----------
```


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Code run is managed with a shell script

In examples/interchange-instability/runcase.sh

Two cases are run by the script, for different values of curvature radius

R=1 m

R=10 m

runcase.sh – emacs@hyperion0.llnl.gov

File Edit Options Buffers Tools Insert Help

```
#!/bin/sh

NO_ARGS=0
OPTERROR=65

if [ $# -eq "$NO_ARGS" ]  # Script invoked with no command-line args?
then
    ##MPIEXEC="mpirun -np "
    MPIEXEC="srun -n "
    NP=4
fi
# Usage: scriptname -options
# Note: dash (-) necessary


while getopts ":n:np" Option
do
  case $Option in
    n ) MPIEXEC="mpirun -np";NP=$OPTARG;;
    * ) ;;   # DEFAULT
  esac
done


#-compile/build local executable
make

#-run the case
echo Running with NP = $NP

rm -fr data
ln -s data_1 data
$MPIEXEC $NP ./2fluid

rm -fr data
ln -s data_10 data
$MPIEXEC $NP ./2fluid


#-check the result
#idl runidl.pro
```

--:-- runcase.sh (Shell-script[sh])--L43--All----

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Options file BOUT.inp is used to change basic physics and numerical options without recompiling physics model source file 2fluid.cxx

BOUT.inp - emacs@hyperion0.llnl.gov

File Edit Options Buffers Tools Help

```
# settings file for BOUT++
#
# Interchange instability in a curved slab
#
#  By default everything in NetCDF.
#  To change to PDB format, change the settings to
#   grid="data/slab.6b5.r10.pdb"
#   dump_format = "pdb"

##################################################
# settings used by the core code

NOUT = 50       # number of time-steps
TIMESTEP = 1e2   # time between outputs

ShiftXderivs = false # use shifted radial derivatives?
TwistShift = false  # use twist-shift condition?

MZ = 65     # number of points in z direction (2^n + 1)
ZMIN = 0.0
ZMAX = 2.8505e-3

MXG = 2
MYG = 2

grid = "slab.6b5.r10.cdl"

dump_format = "nc" # Output format. nc = NetCDF

##################################################
# derivative methods

[ddx]

first = C2
second = C2
upwind = W3

[ddy]

first = C4
second = C4
upwind = W3

[ddz]

first = FFT
```

--:-- BOUT.inp (Fundamental)--L1--Top----------

Beginning of buffer

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Output is processed with IDL script which produces plots, numerical values etc

runidl.pro – emacs@hyperion0.llnl.gov

File Edit Options Buffers Tools Debug IDLWAVE Help

```
.run pdb2idl.pro
.run moment_xyzt.pro

d = collect(path="data_1", var="Ni", x=5, y=30)
moment_xyzt, d, rms=ni1

d = collect(path="data_10", var="Ni", x=5, y=30)
moment_xyzt, d, rms=ni10
tt = collect(path="data_10", var="t_array")
wci = collect(path="data_10", var="wci")
tt = tt[1:*] / wci

ni1 = REFORM(ni1[0,0,1:*])
ni10 = REFORM(ni10[0,0,1:*])

;-compare with original test results (grendel, 31-jan-2007)
 RESTORE, 'orig_test.idl.dat'
 error1=max(abs((ni1orig-ni1)/ni1orig)) + max(abs((ni10orig-ni10)/ni10orig))
 print, "Deviation from original test result is" , error1*1e2, " %"

set_plot, 'PS'
device, file='interchange_inst_test.ps'
safe_colors, /first

xtit='t, s' & ytit='rms <Ni>' & tit='Interchange instability test'
plot, tt, ni1, /yl, psym=4, xtit=xtit, ytit=ytit, tit=tit, chars=1.5,col=1, xticks=3
 oplot, tt, 1e-4*exp(tt*2.2e5),col=1
 oplot, tt, ni10, psym=4,col=1
 oplot, tt, 1e-4*exp(tt*6.3e4),col=1, lin=2

 oplot, tt, ni1orig,psym=7,col=1
 oplot, tt, ni10orig, psym=7,col=1

 xyouts, 7e-5, 0.15, "R0=10 m",col=1
 xyouts, 4e-5, 1e2, "R0=1 m",col=1

; calculate growth rates

n1g0 = MEAN(DERIV(tt, ALOG(ni1orig)))
n1g  = MEAN(DERIV(tt, ALOG(ni1)))

n1d = 100. * ABS(n1g0 - n1g) / n1g0

n10g0 = MEAN(DERIV(tt, ALOG(ni10orig)))
n10g  = MEAN(DERIV(tt, ALOG(ni10)))

n10d  = 100. * ABS(n10g0 - n10g) / n10g0
```

--:-- runidl.pro (IDLWAVE Abbrev Fill)--L47--Top----------

Beginning of buffer

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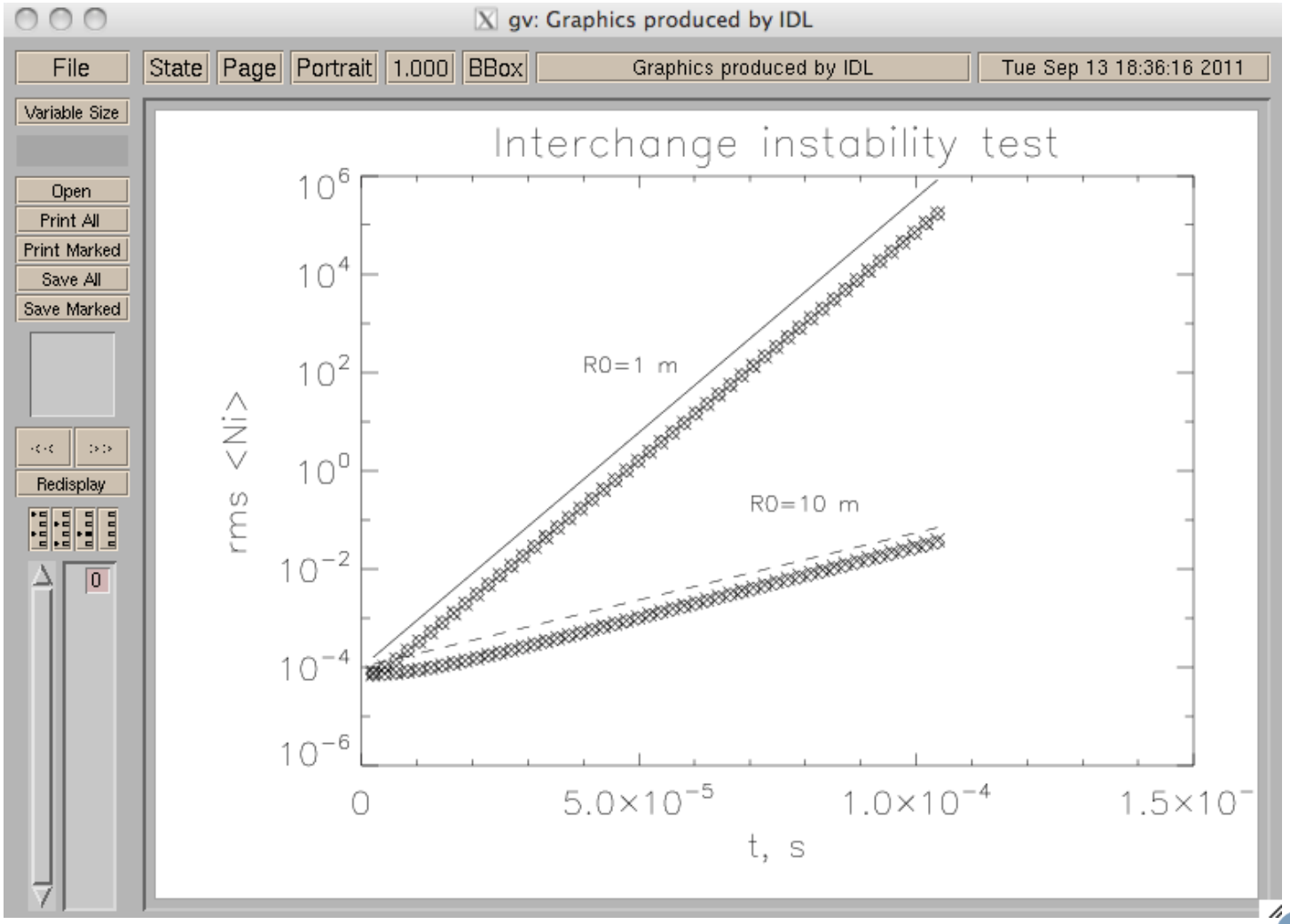
BOUT++ correctly reproduces analytic answer for the interchange mode growth rate!

In examples/interchange-instability/interchange_inst_test.ps



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Suggested exercises for practice

- **Basic**
  - **Run the interchange-instability case**
  - **Run the IDL processing script**
  - **View the plot**

```
cd <path>/BOUT-1.0/examples/interchange-instability
source runcase.sh
idl runidl.pro
gv interchange_inst_test.ps
```

- **Intermediate**
  - **Read/understand/modify the source file 2fluid.cxx and scripts runcase.sh, runidl.pro**
- **Advanced**
  - **Try setting up a new simple case from scratch**

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