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## Simulating experimental techniques: Kelvin Probe Force Microscopy NanoTechnology-NN22

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Horizon 2020

*NanoTechnology-NN22*



# Simulating experimental techniques : Kelvin Probe Force Microscopy

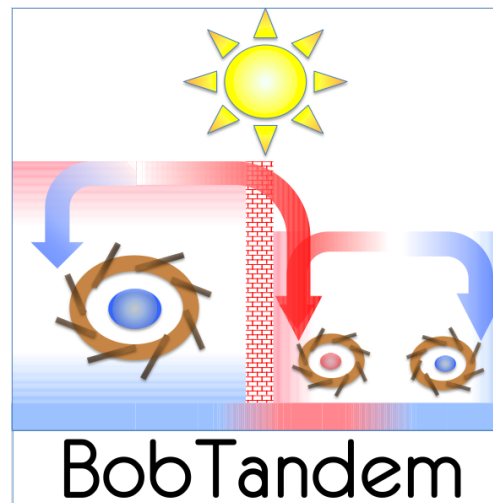
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<sup>4</sup> Silvaco Europe, Cambridge, UK



CentraleSupélec



## *Summary*

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- Kelvin probe force microscopy : an introduction
- Analytical and numerical methods
- Simulating the experiment

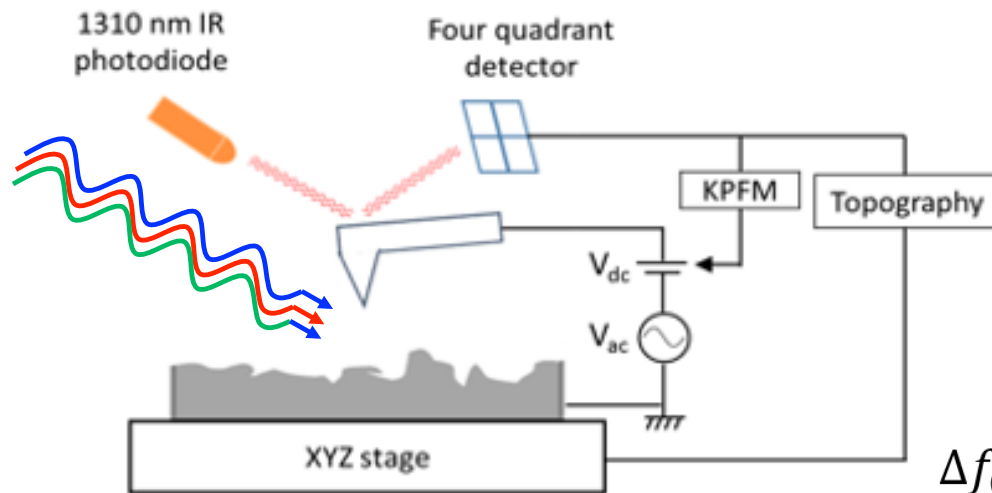
# *Kelvin probe force microscopy*

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- Measurement of **surface voltage** versus **incident photon energy**
- **Surface Photovoltage embodiment** : Light signal minus dark as a function of photon energy
- Semiconductor materials (surfaces, interfaces, and bulk) and optoelectronic devices
- Contactless technique and non destructive
- No need sample preparation or junction fabrication
- Information extracted : semiconductor type (n or p), electronic transitions (band-to-band, defect-band), **diffusion length**, **minority carrier-lifetime**, open-circuit voltage...
- Challenge : Analysis of surface techniques dominated by surface defects

=> Solution : Modelling

# Kelvin probe force microscopy : The technique



Two-pass mode scanning :

- 1<sup>st</sup> topography
- 2<sup>nd</sup> KPFM

## Amplitude Modulation

$$F_{\omega} = \frac{\partial C}{\partial z} (V_{DC} - CPD) V_{AC} \cos(\omega t)$$

## Frequency Modulation

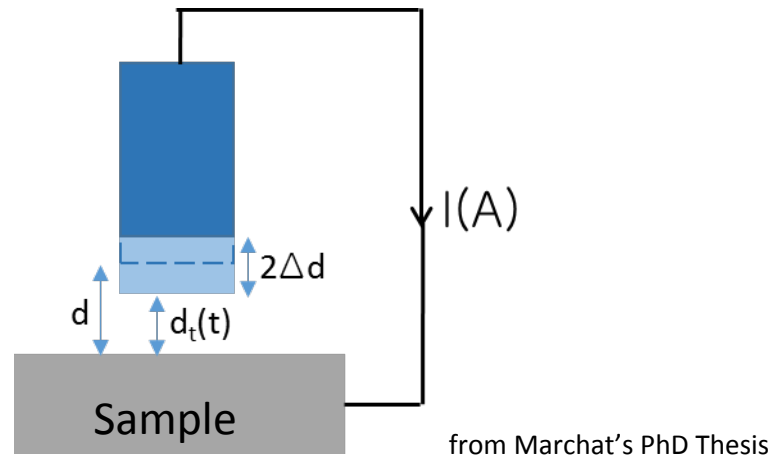
$$\Delta f_0(\omega) \propto \frac{\partial F_{\omega}}{\partial z} = \frac{\partial^2 C}{\partial z^2} (V_{DC} - CPD) V_{AC} \sin(\omega t)$$

$$CPD_{KPFM} = \frac{(W_{sonde} - W_{surf})}{q}$$

# *Kelvin probe force microscopy : basic principle*

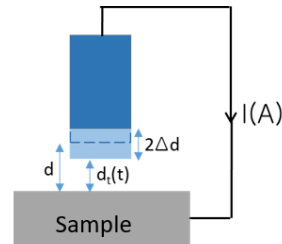
---

**DC light**



Vibrating probe/capacitor :  
**Kelvin probe**

# Kelvin probe force microscopy : CPD and SPV



Surface Voltage or Contact Potential Difference (CPD)  
=> Work Function ( $W_F$ )

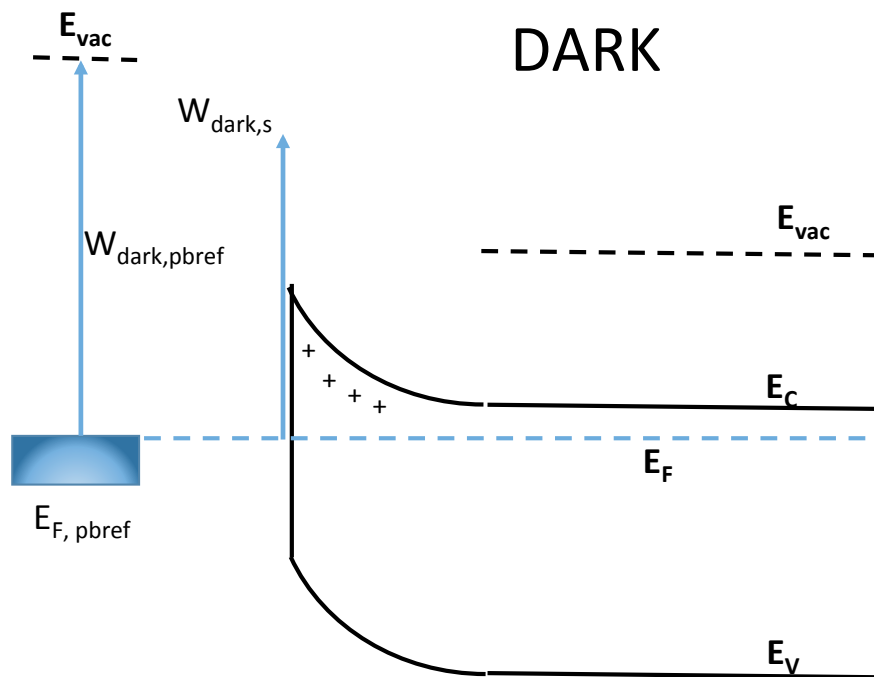


Lamp and Monochromator

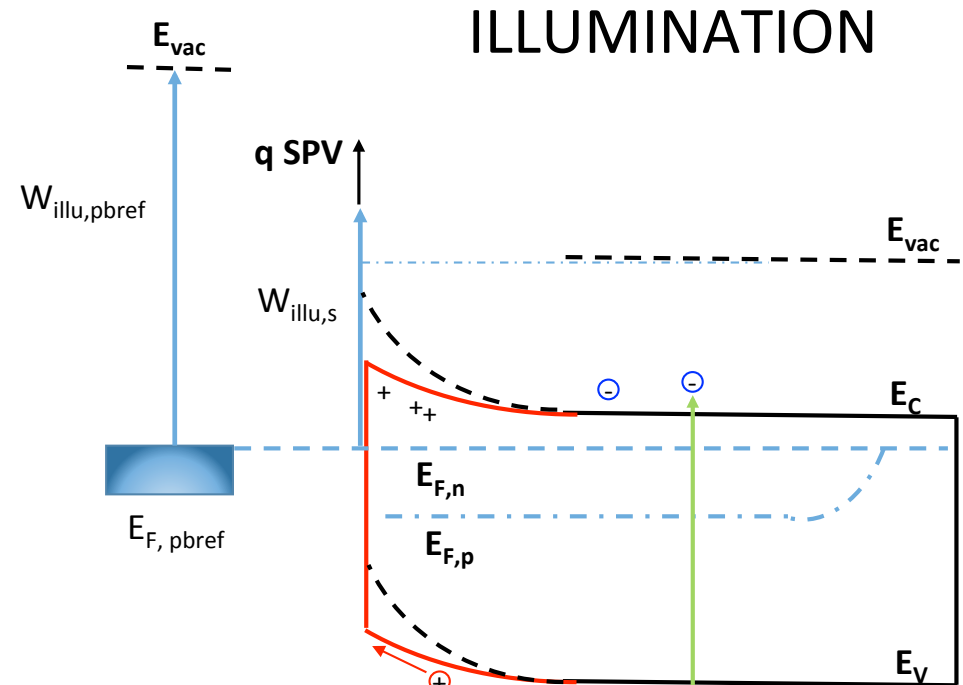


SPV-Spectroscopy

# Kelvin probe force microscopy : Surfaces



$$q \text{ CPD}_{\text{dark}} = W_{\text{dark, pbref}} - W_{\text{dark, s}}$$



$$q \text{ CPD}_{\text{illu}} = W_{\text{illu, pbref}} - W_{\text{illu, s}}$$

$$\text{SPV} = (\text{CPD}_{\text{illu}} - \text{CPD}_{\text{dark}}) = - (W_{\text{illu, s}} - W_{\text{dark, s}}) / q = (E_{F, p} - E_{F, n}) / q$$

- Dark :** Work function affected by surface states / charges  
**Light :** Signal modified by QFL splitting



## *Analytical / numerical models sketch:*

---

### *Analytical model :*

- Charge :  $q(p-n+N_d-N_a)$  – electrons, holes, donors, acceptors
- Solve Poisson equation ([Matlab](#))

=> Surface field as a function of acceptor and donor defects

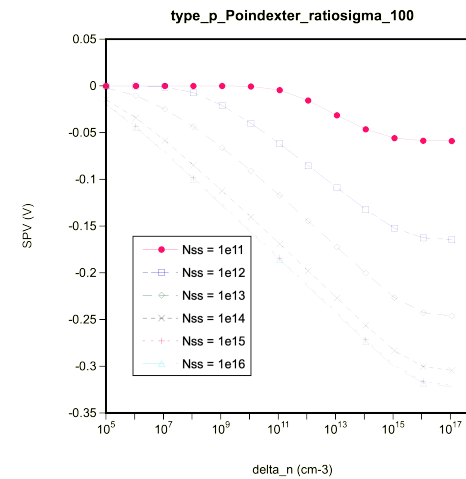
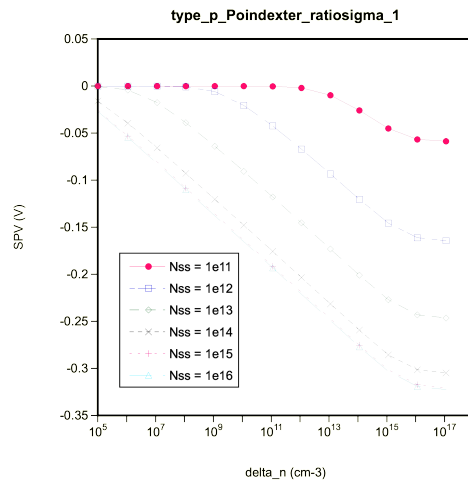
### *Numerical model :*

- Solve current and continuity numerically ([Silvaco](#))
- Arbitrary (within reason) defect distributions

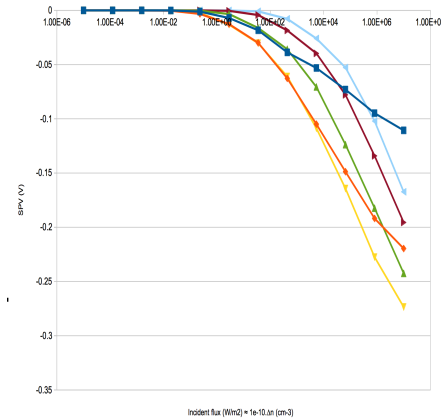
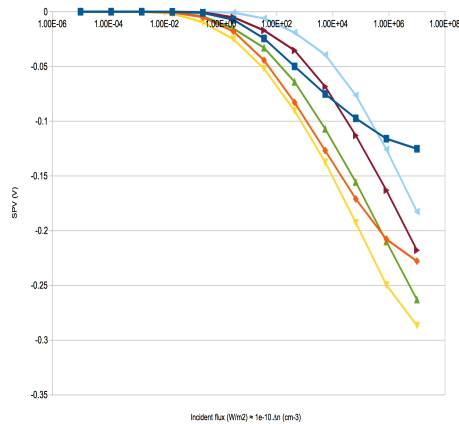
### *The object :*

- Bulk silicon
- 2D surface acceptor and donor defect states (analytical)
- 3D surface acceptor and donor defect states (numerical)

# Analytical : equal trap capture cross section



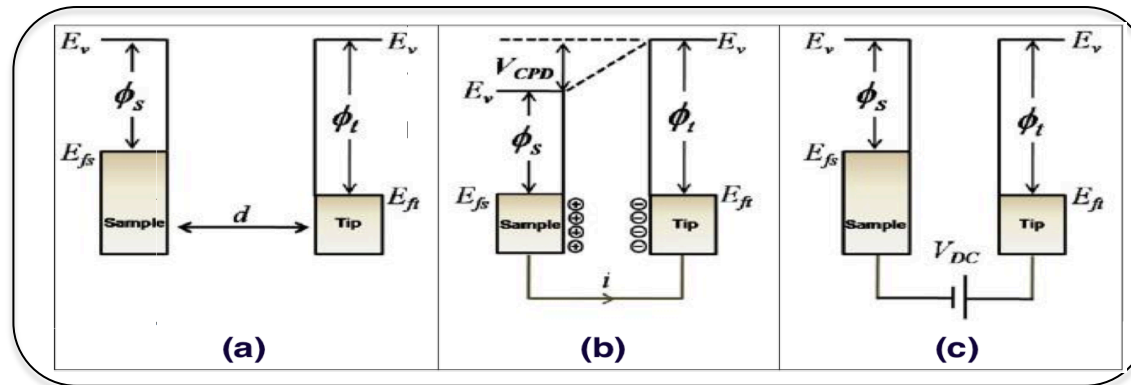
# Numerical : equal trap capture cross section



=> qualitative agreement in trends – future work.



# Reminder : Kelvin Probe Force Microscopy KPFM



Kelvin probe force microscopy: work function measurement.

(a) Sample and tip far apart.

(b) Sample and tip in contact: Fermi levels align, current flows. The vacuum level step:  $V_{CPD}$

(c) External applied bias equal to  $V_{CPD}$  equilibrates vacuum levels.

=> Known KPFM tip vacuum and  $V_{CPD}$  levels gives sample work function.

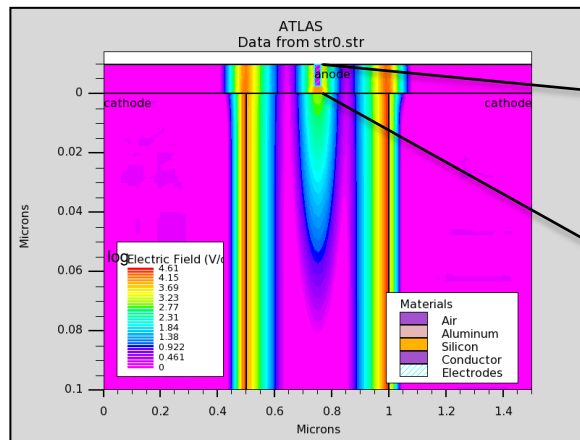


Fig. 2

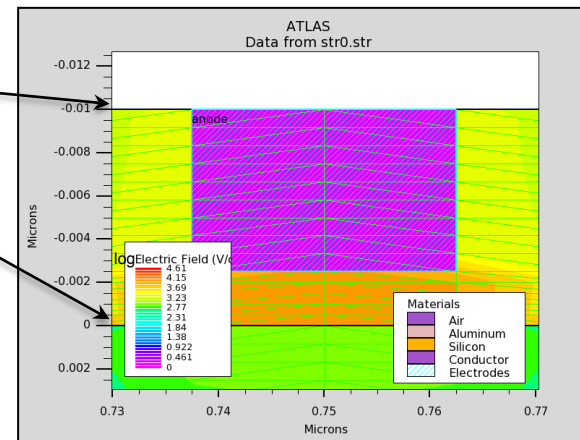
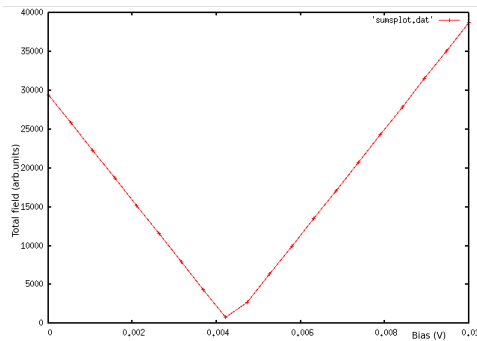
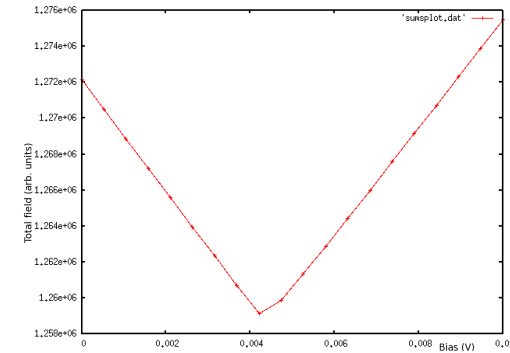


Fig. 3

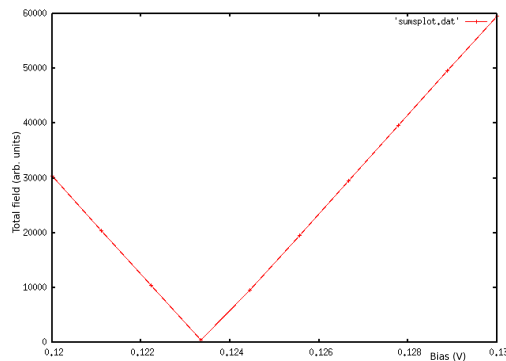
# Solution method : minimum tip / probe field



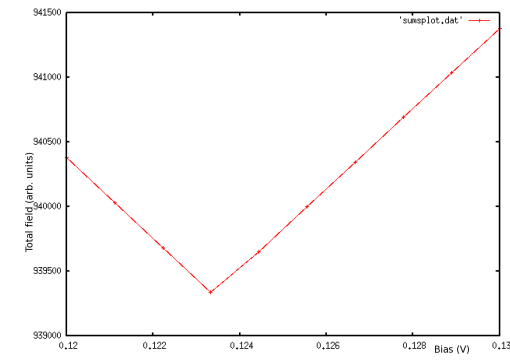
No defects: "Gap" field as a function of applied bias:  
Minimum  $\approx 4\text{meV}$



"No defects: Bulk" field as a function of applied bias:  
Minimum  $\approx 4\text{meV}$



"Gap" field as a function of applied bias: Minimum  $\approx 50\text{meV}$



"Bulk" field as a function of applied bias: Minimum  $\approx 50\text{meV}$

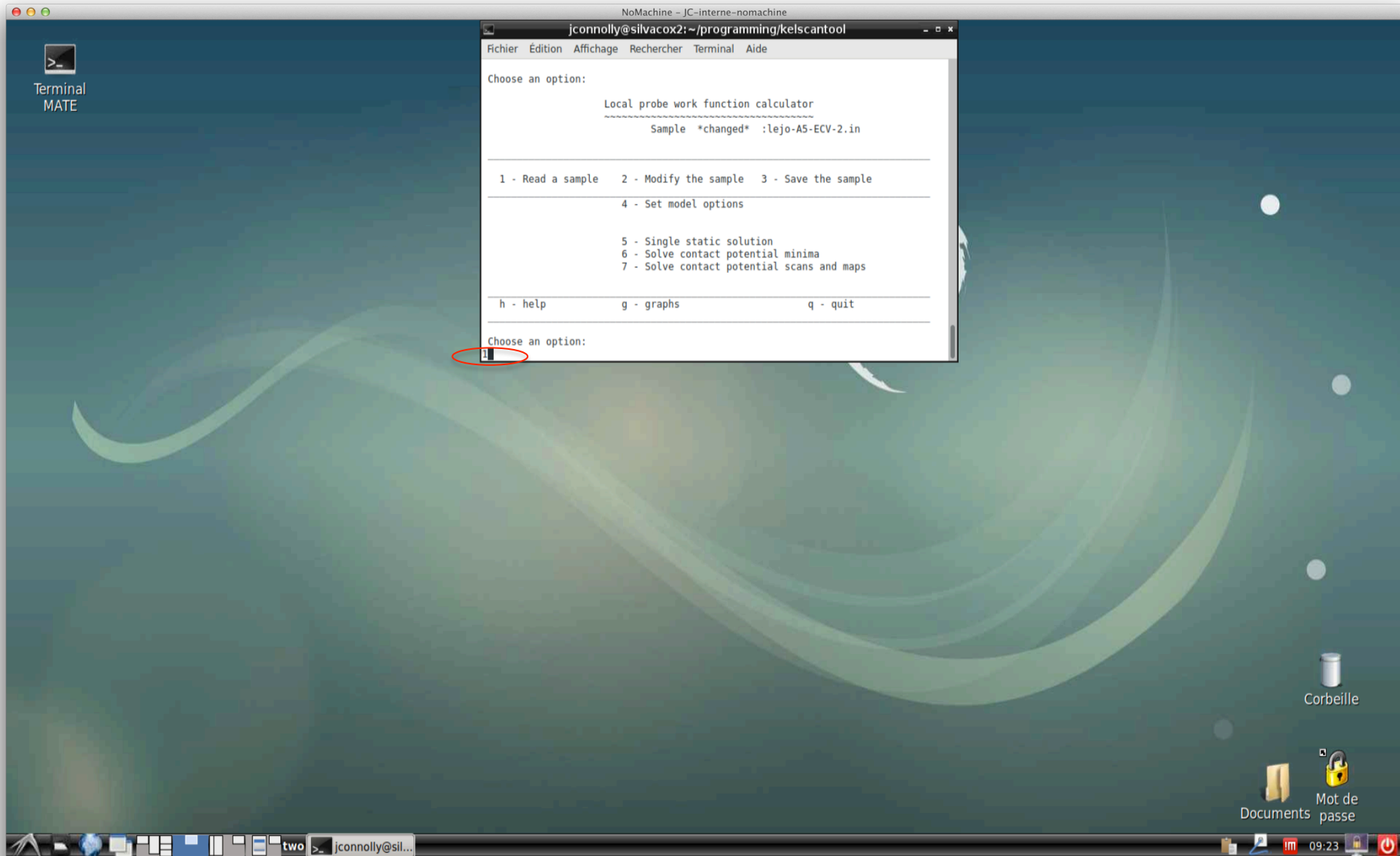
"Gap" / "Bulk" methods for Vcpd comparison :

- Little difference for these doping levels
- Differences nevertheless expected

**$\Rightarrow$  Rapid "gap" or spot method preferred**

# Kelscan demonstration

Splash screen choice "1" – choose sample



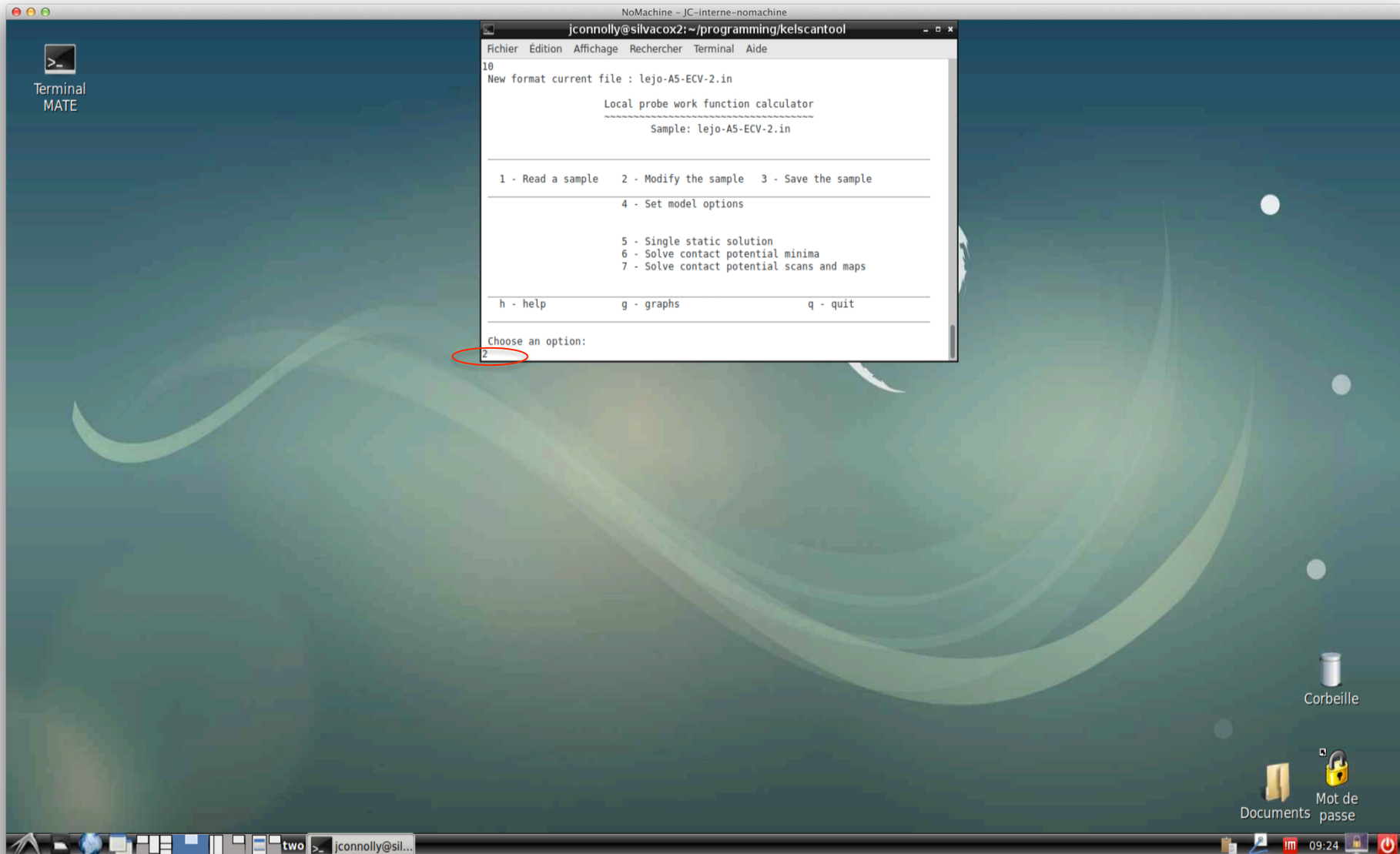
# Kelscan demonstration

## Sample choice



# Kelscan demonstration

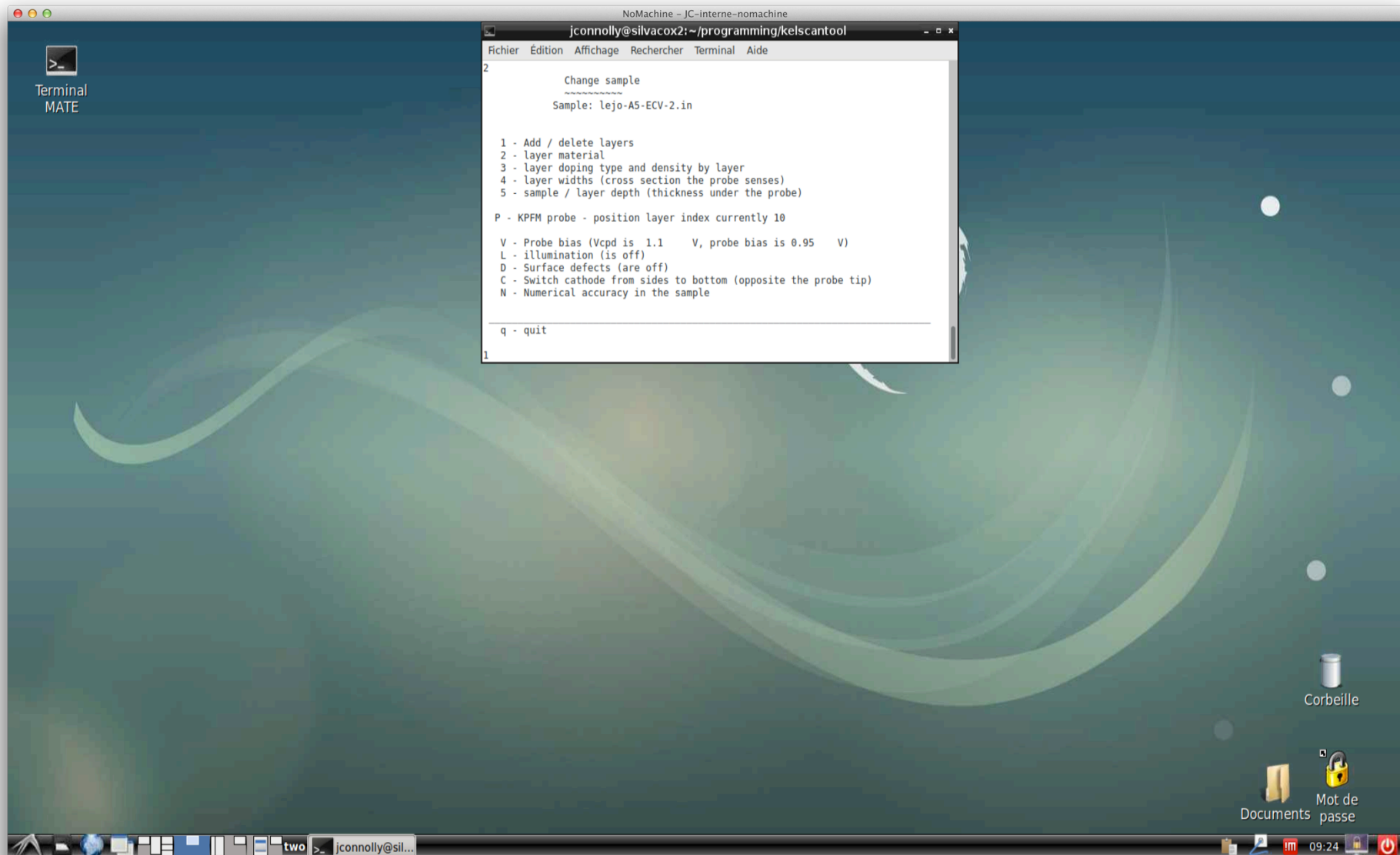
## Sample modification menu





# Kelscan demonstration

The **sample file format**: Saves all simulation parameters shown here.  
Silvaco compatible : can be directly run by Silvaco Deckbuild



The screenshot shows a Linux desktop environment with a terminal window open. The terminal window title is "jconnolly@silvaco2: ~/programming/kelscantool". The terminal content displays the following text:

```
2
Change sample
-----
Sample: lejo-A5-ECV-2.in

1 - Add / delete layers
2 - layer material
3 - layer doping type and density by layer
4 - layer widths (cross section the probe senses)
5 - sample / layer depth (thickness under the probe)

P - KPFM probe - position layer index currently 10

V - Probe bias (Vcpd is 1.1 V, probe bias is 0.95 V)
L - illumination (is off)
D - Surface defects (are off)
C - Switch cathode from sides to bottom (opposite the probe tip)
N - Numerical accuracy in the sample

q - quit
1
```

# Kelscan demonstration

Sample properties of multi-layer sample simulating Lejo Joseph doping profile measurement

Terminal  
MATE

```
NoMachine - JC-interne-nomachine
jconnolly@silvacox2: ~/programming/kelscantool
Fichier Edition Affichage Rechercher Terminal Aide

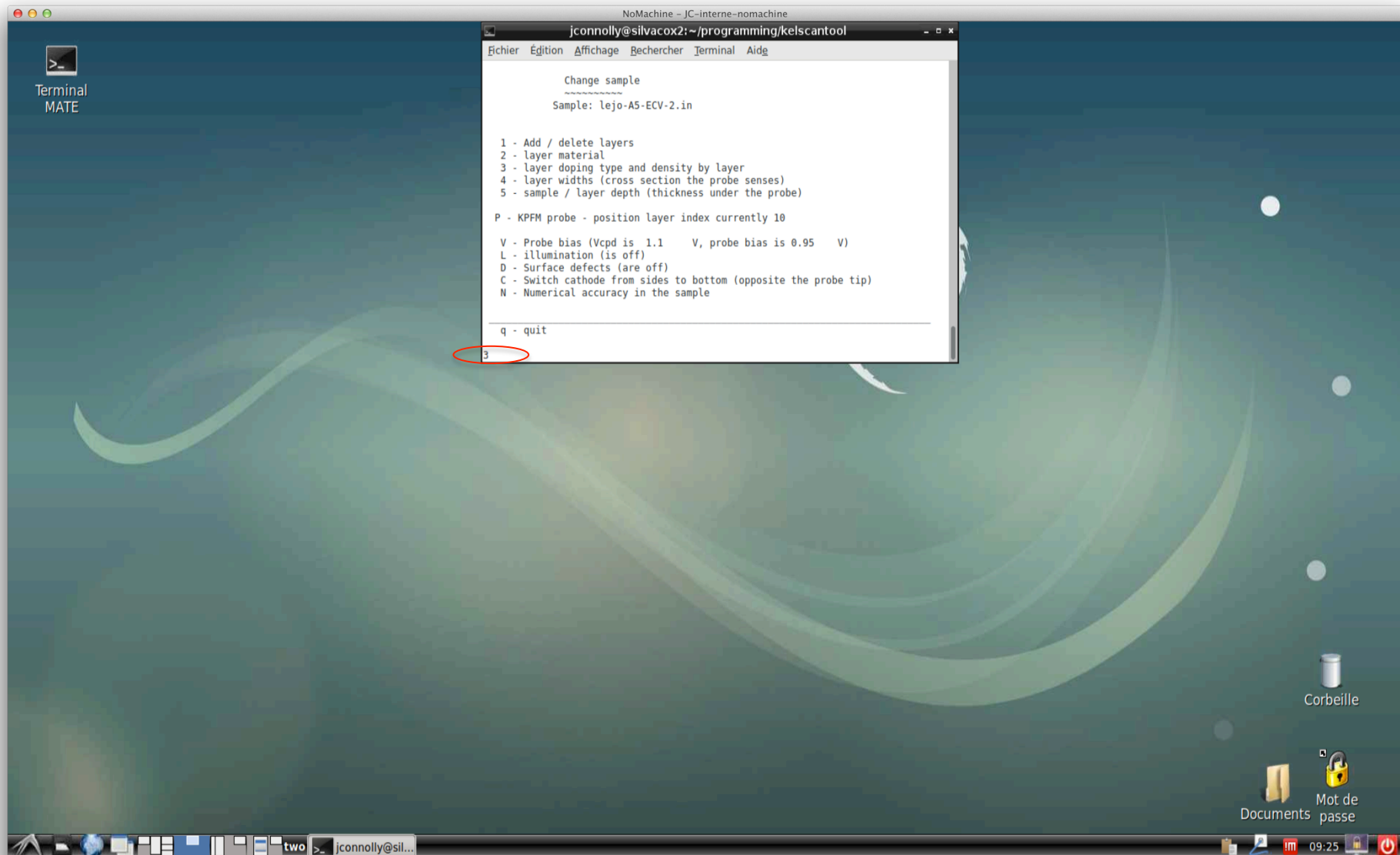
Index   Width (um) Doping (/cm3) Type (p or n) Material (name)
-----
1)      0.750E-01  0.280E+20    p             silicon
2)      0.750E-01  0.330E+20    p             silicon
3)      0.750E-01  0.313E+20    p             silicon
4)      0.750E-01  0.295E+20    p             silicon
5)      0.750E-01  0.249E+20    p             silicon
6)      0.750E-01  0.184E+20    p             silicon
7)      0.750E-01  0.133E+20    p             silicon
8)      0.750E-01  0.723E+19    p             silicon
9)      0.750E-01  0.173E+19    p             silicon
10)     0.750E-01  0.261E+18    p             silicon
11)     0.750E-01  0.108E+18    n             silicon
12)     0.750E-01  0.178E+18    n             silicon
13)     0.750E-01  0.180E+18    n             silicon
14)     0.750E-01  0.150E+18    n             silicon
15)     0.750E-01  0.122E+18    n             silicon
16)     0.750E-01  0.214E+18    n             silicon
17)     0.750E-01  0.372E+16    n             silicon
18)     0.750E-01  0.512E+16    n             silicon
19)     0.750E-01  0.645E+16    n             silicon
20)     0.750E-01  0.117E+18    n             silicon

Add or delete (existing layers will be copied) ? (a/d or quit)
```

Corbeille  
Documents Mot de passe  
09:49

# Kelscan demonstration

## Doping levels



```

NoMachine - JC-interne-nomachine
jconnolly@silvacox2: ~/programming/kelscantool
Fichier Edition Affichage Rechercher Terminal Aide

Change sample
-----
Sample: lejo-A5-ECV-2.in

1 - Add / delete layers
2 - layer material
3 - layer doping type and density by layer
4 - layer widths (cross section the probe senses)
5 - sample / layer depth (thickness under the probe)

P - KPFM probe - position layer index currently 10

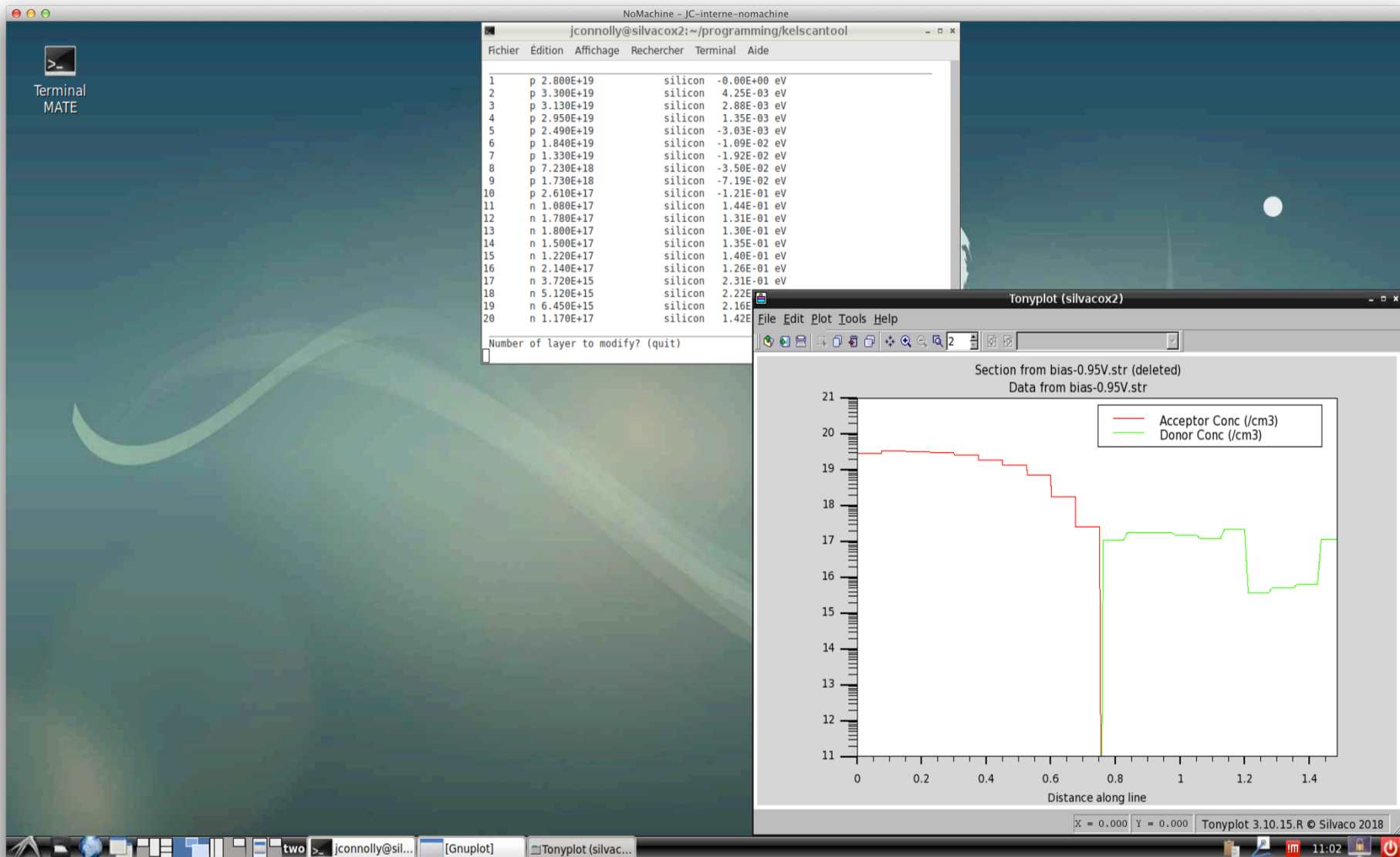
V - Probe bias (Vcpd is 1.1 V, probe bias is 0.95 V)
L - illumination (is off)
D - Surface defects (are off)
C - Switch cathode from sides to bottom (opposite the probe tip)
N - Numerical accuracy in the sample

q - quit
3

```

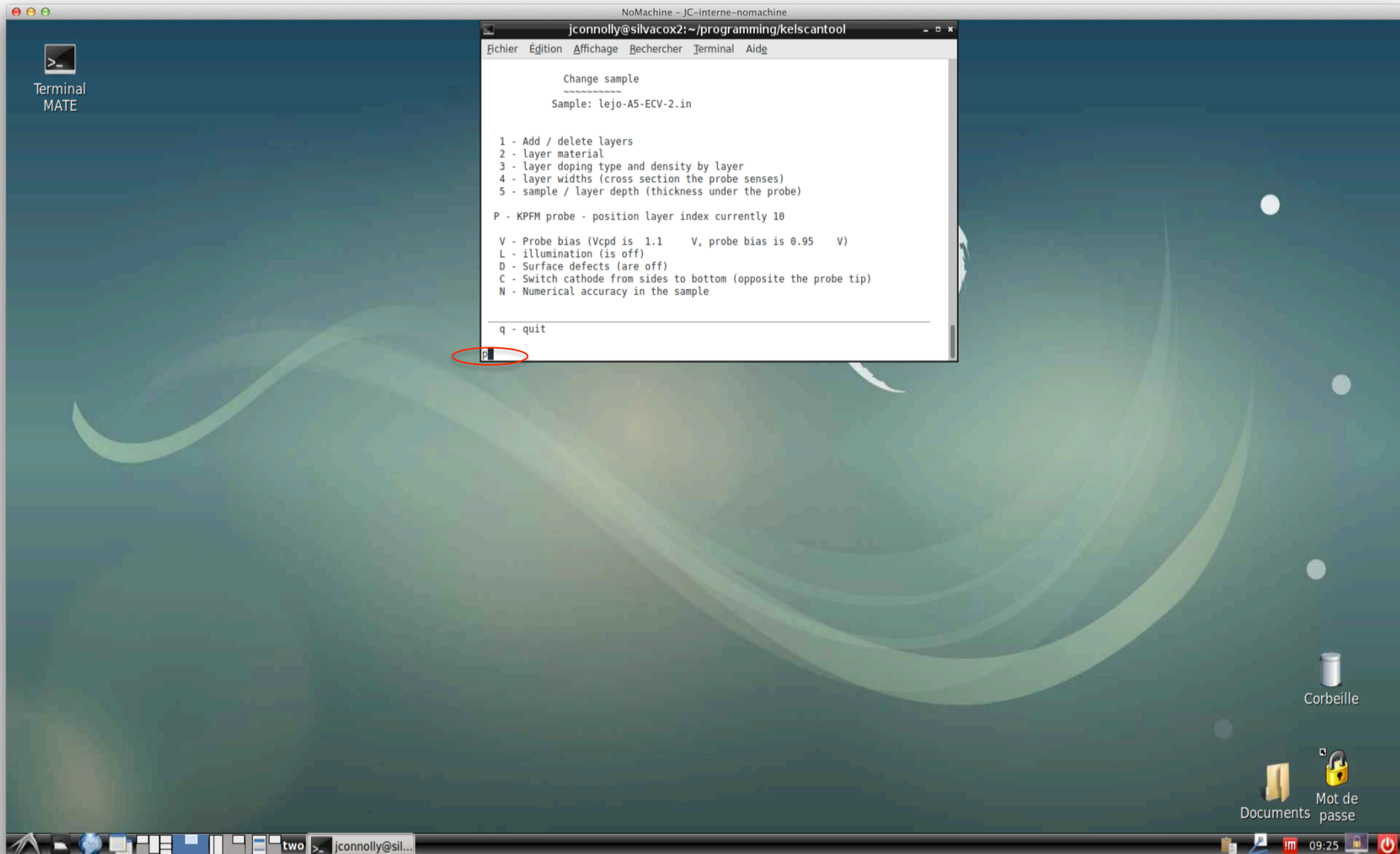
# Kelscan demonstration

## Doping levels and tonyplot doping graph



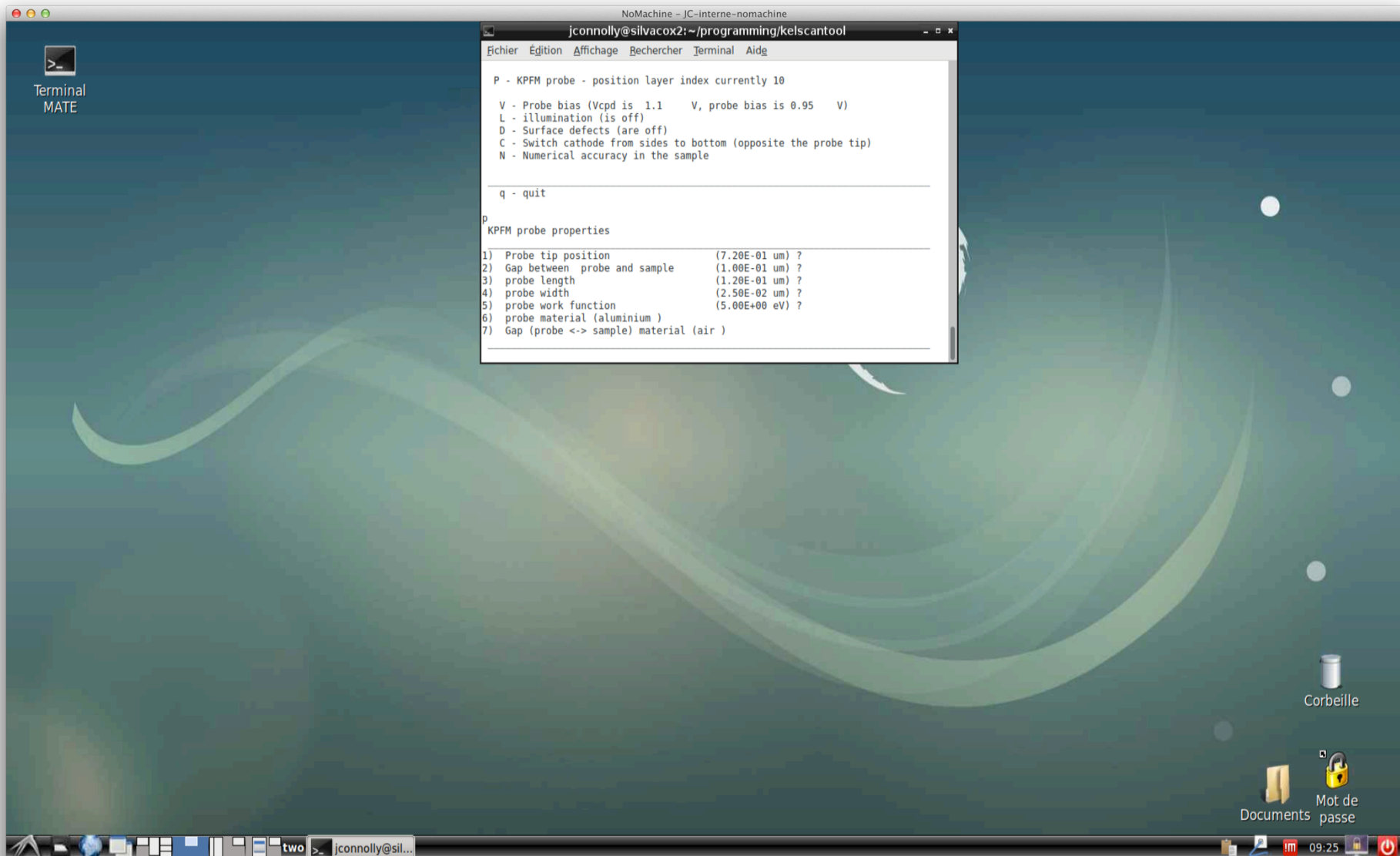
# Kelscan demonstration

## Sample modify – KPFM probe



# Kelscan demonstration

## Sample modify – KPFM probe properties



```
Terminal
MATE

NoMachine - JC-interne-nomachine
jconnolly@silvacox2:~/programming/kelscantool
Fichier Edition Affichage Rechercher Terminal Aide

P - KPFM probe - position layer index currently 10

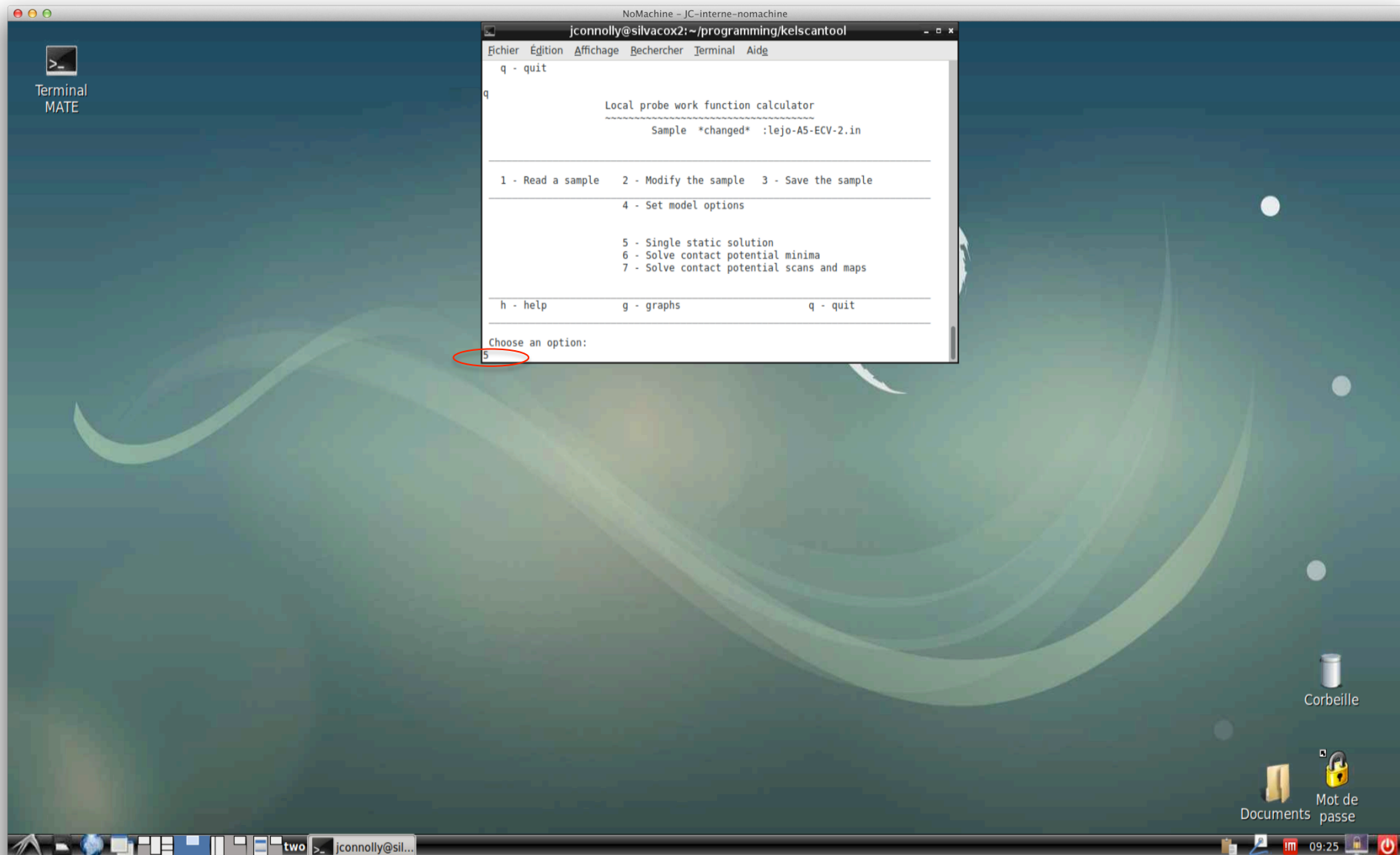
V - Probe bias (Vcpd is 1.1 V, probe bias is 0.95 V)
L - illumination (is off)
D - Surface defects (are off)
C - Switch cathode from sides to bottom (opposite the probe tip)
N - Numerical accuracy in the sample

q - quit

P
KPFM probe properties
1) Probe tip position (7.20E-01 um) ?
2) Gap between probe and sample (1.00E-01 um) ?
3) probe length (1.20E-01 um) ?
4) probe width (2.50E-02 um) ?
5) probe work function (5.00E+00 eV) ?
6) probe material (aluminium)
7) Gap (probe <-> sample) material (air )
```

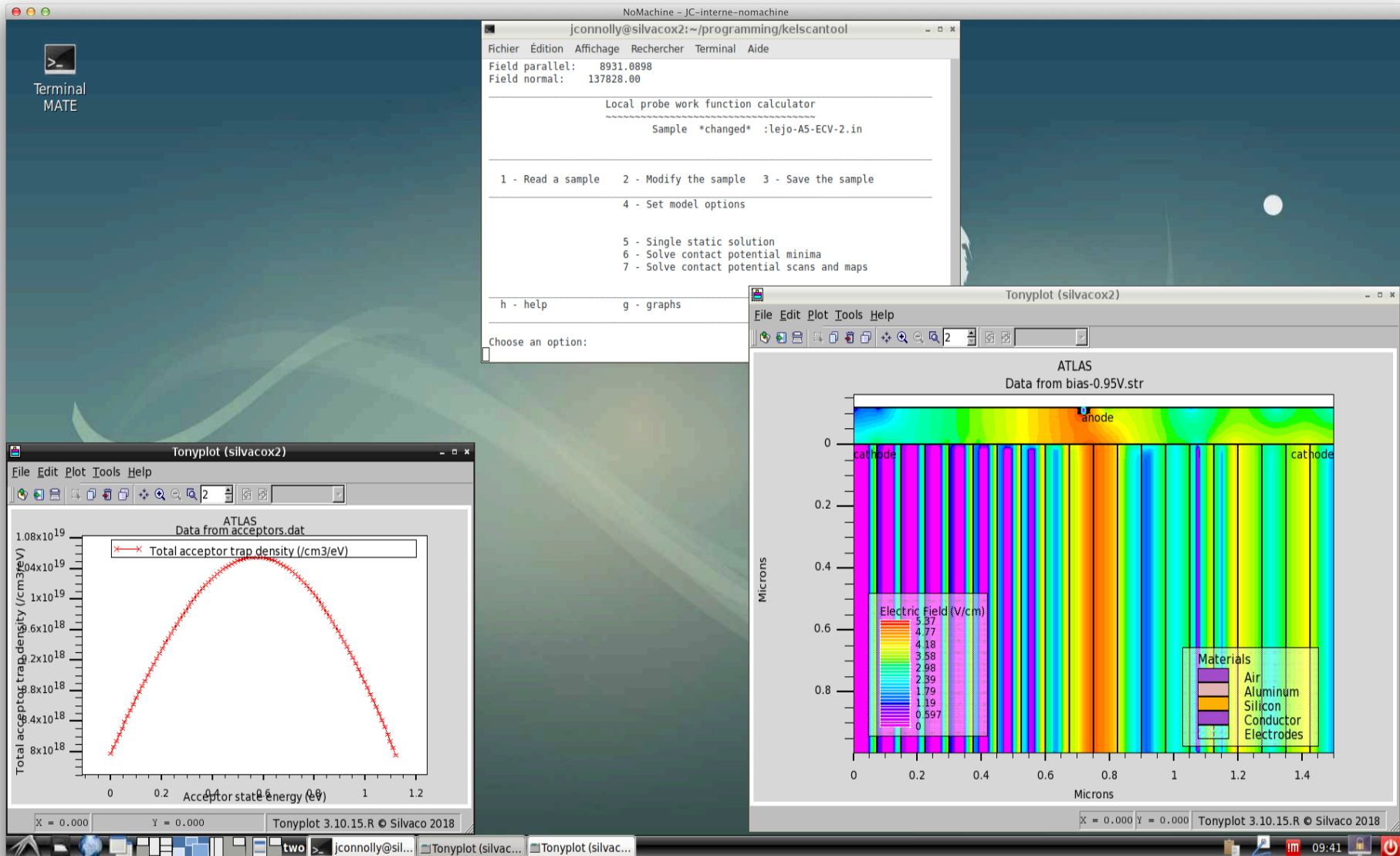
# Kelscan demonstration

Single solution of structure for specified structure including probe position, defects, and illumination



# Kelscan demonstration

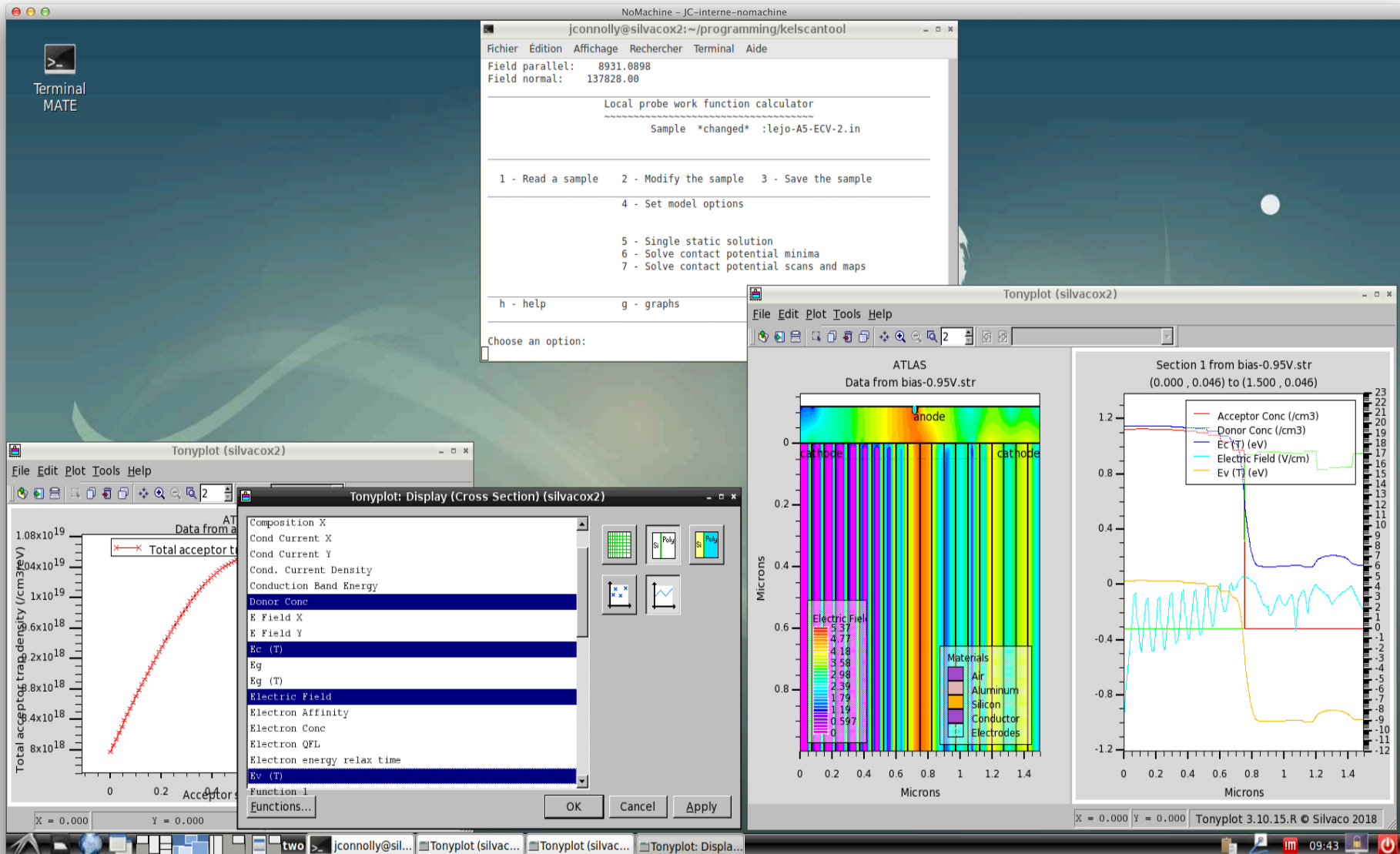
Single solution showing acceptor type defects and fields in a multilayer structure





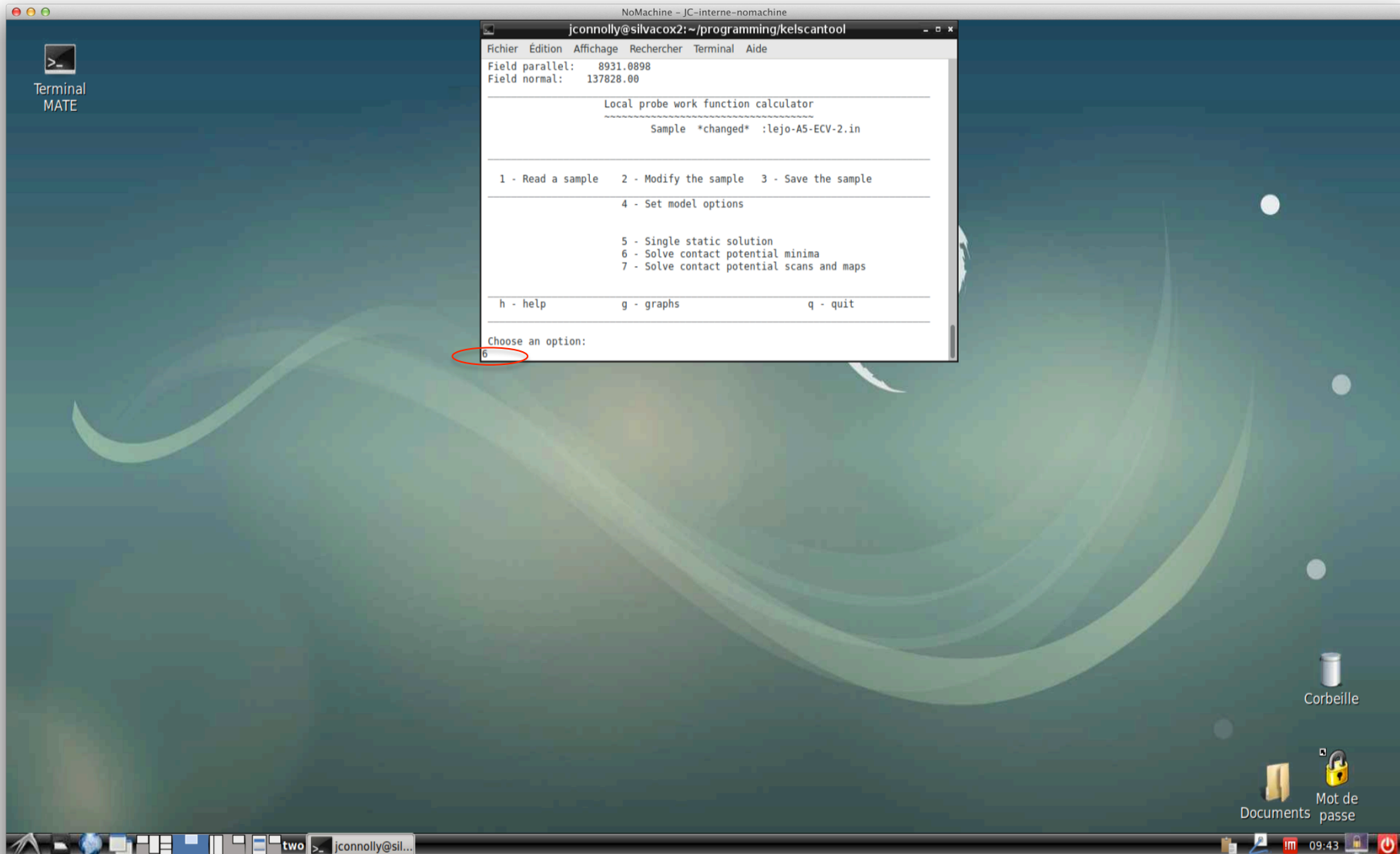
# Kelscan demonstration

Single solution Tonyplot parameter lists – here band structure and field



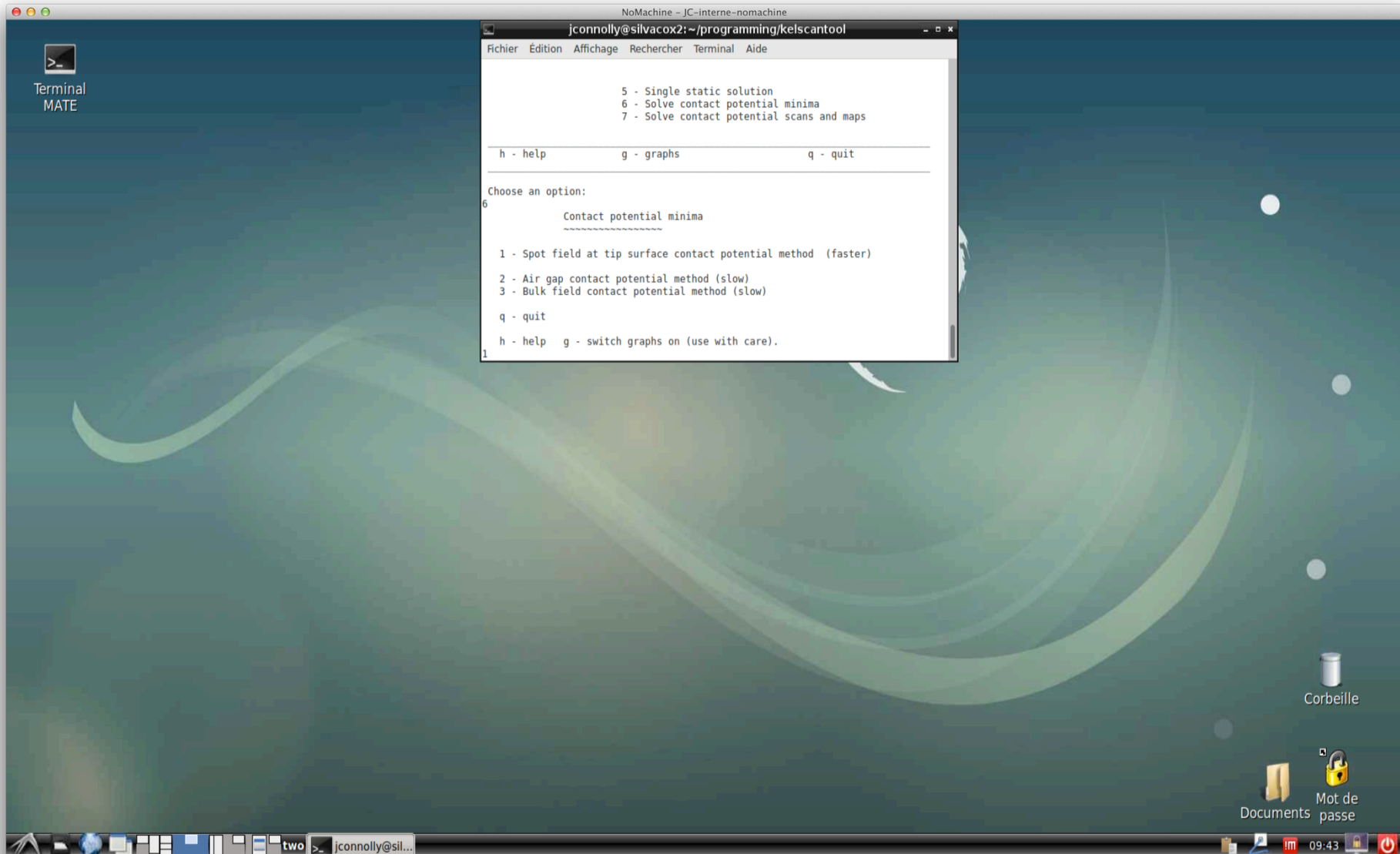
# Kelscan demonstration

The prime function : the contact potential solution



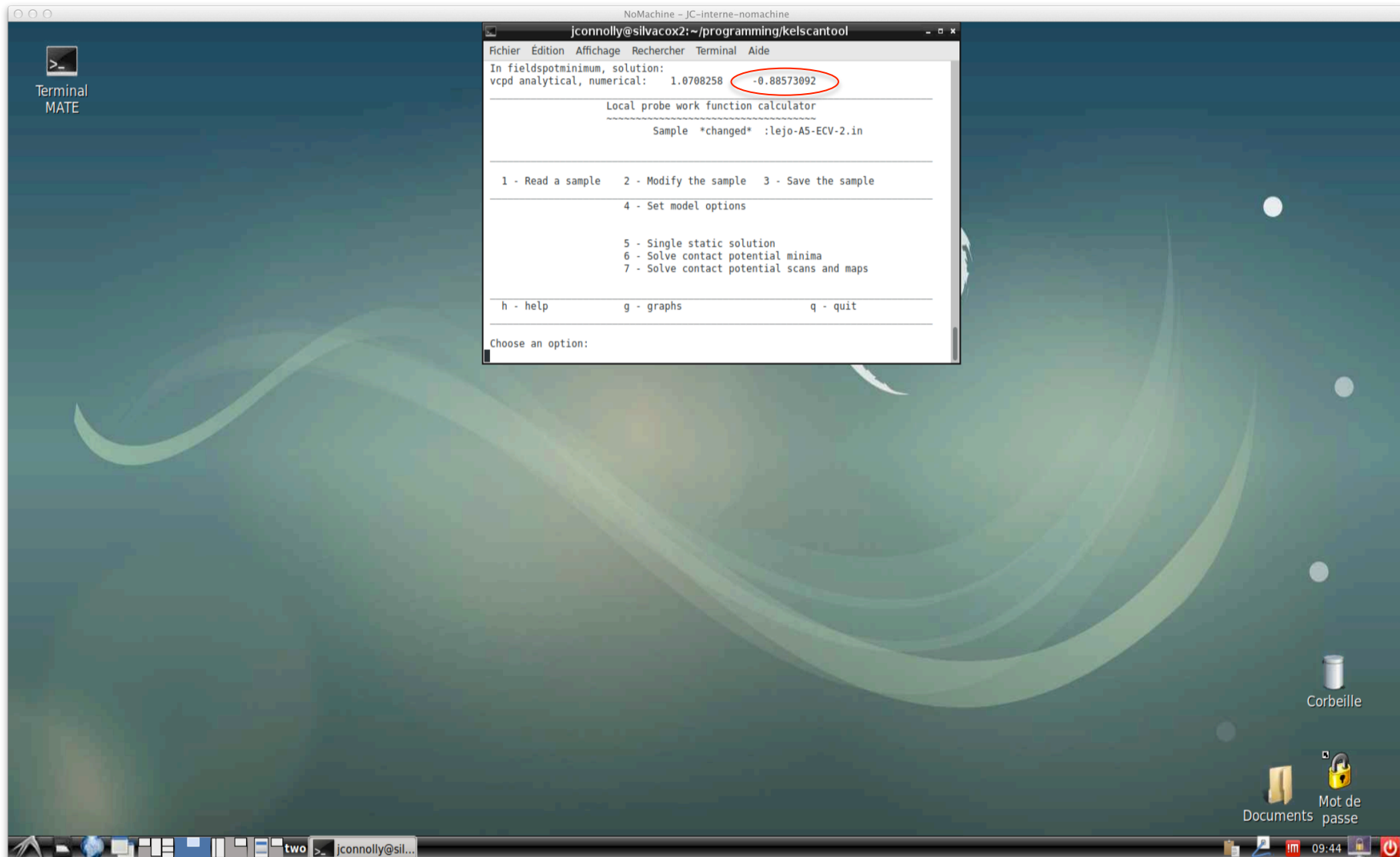
# Kelscan demonstration

A range of methods for flexibility: Spot method preferred (Speed).



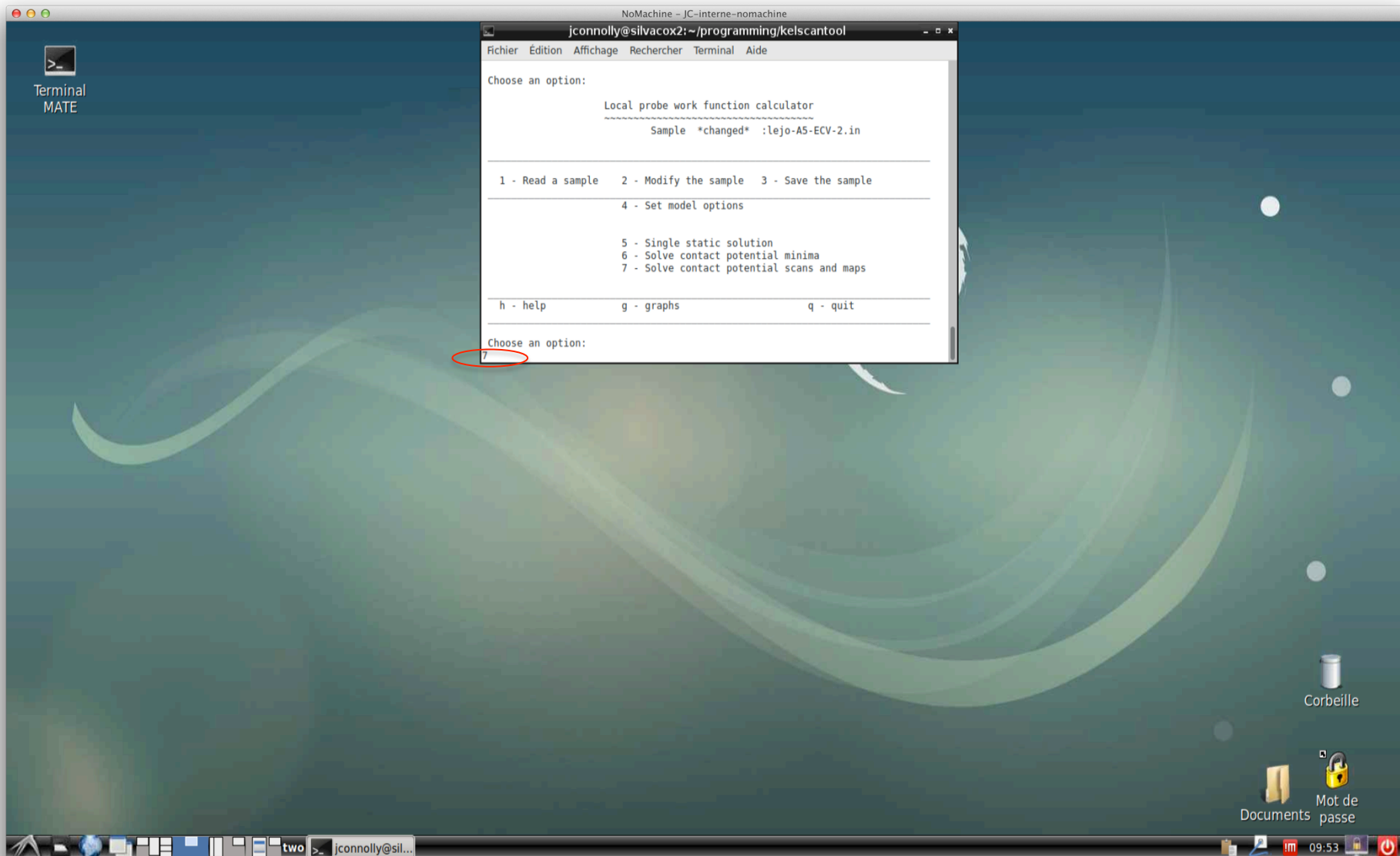
# Kelscan demonstration

Contact potential evaluated from two points (assumes linearity)



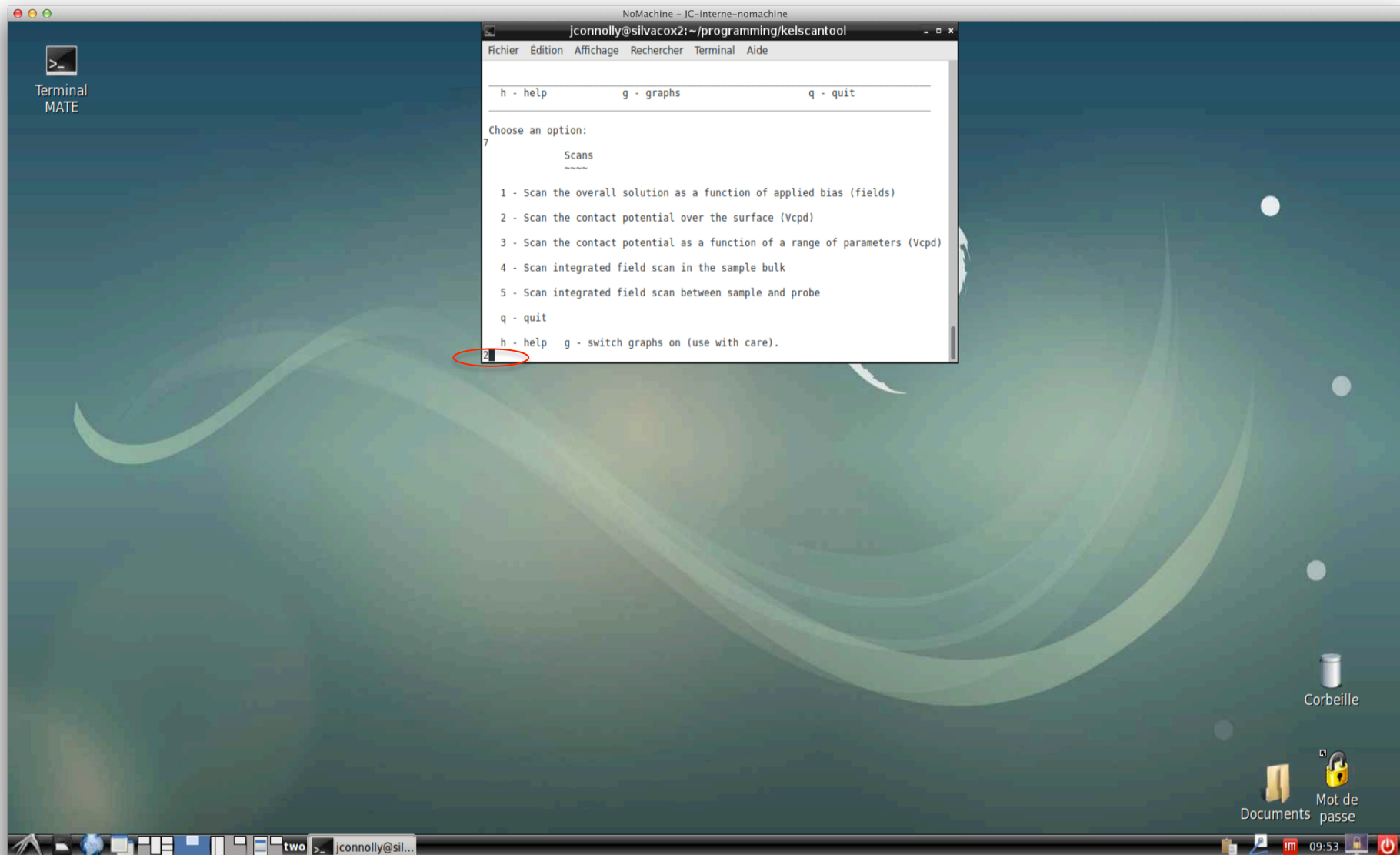
# Kelscan demonstration

## Contact potential scans



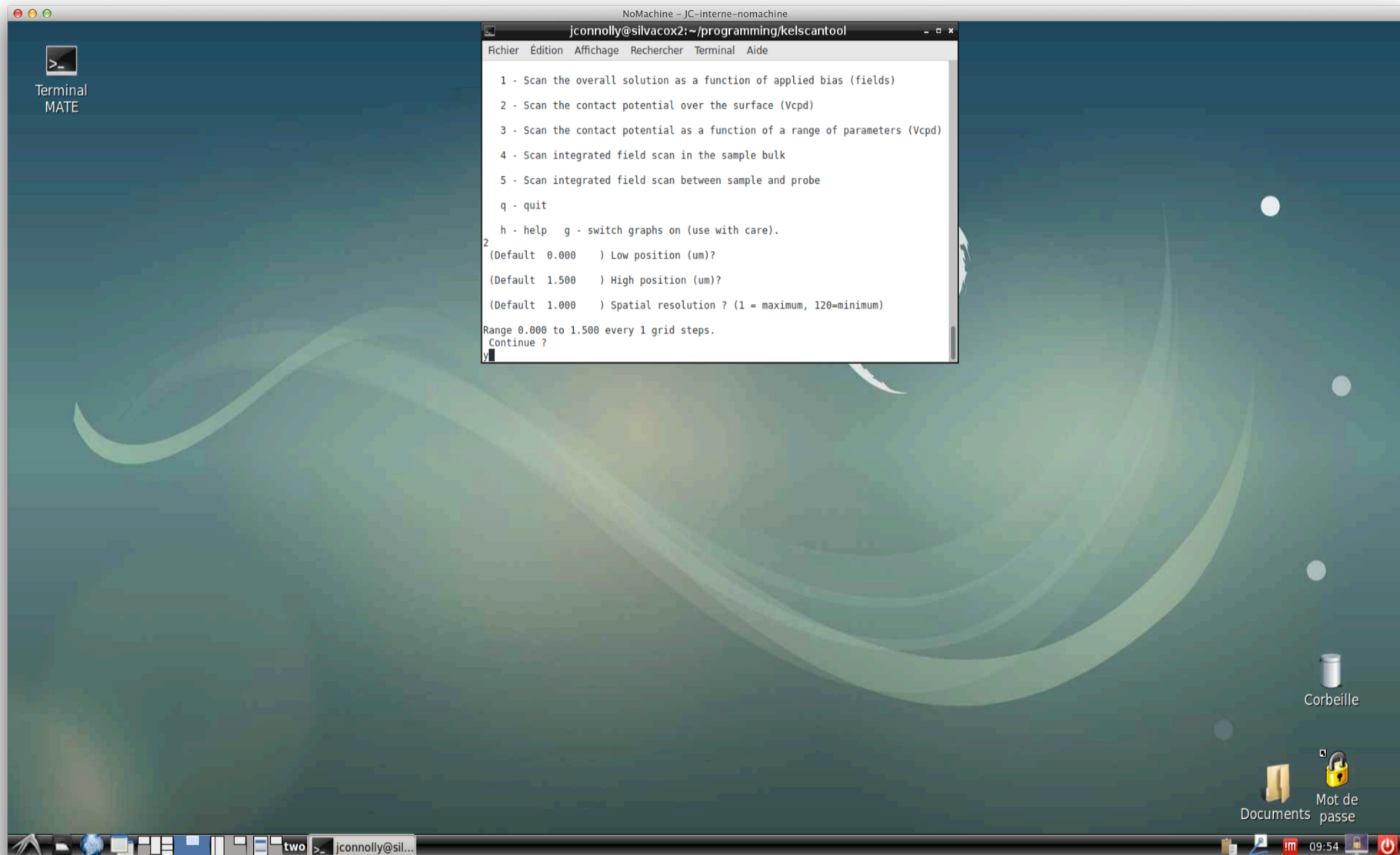
# Kelscan demonstration

## Contact potential scan over the surface



# Kelscan demonstration

Contact potential scan over the surface : range and resolution (integer grid spacing)



```

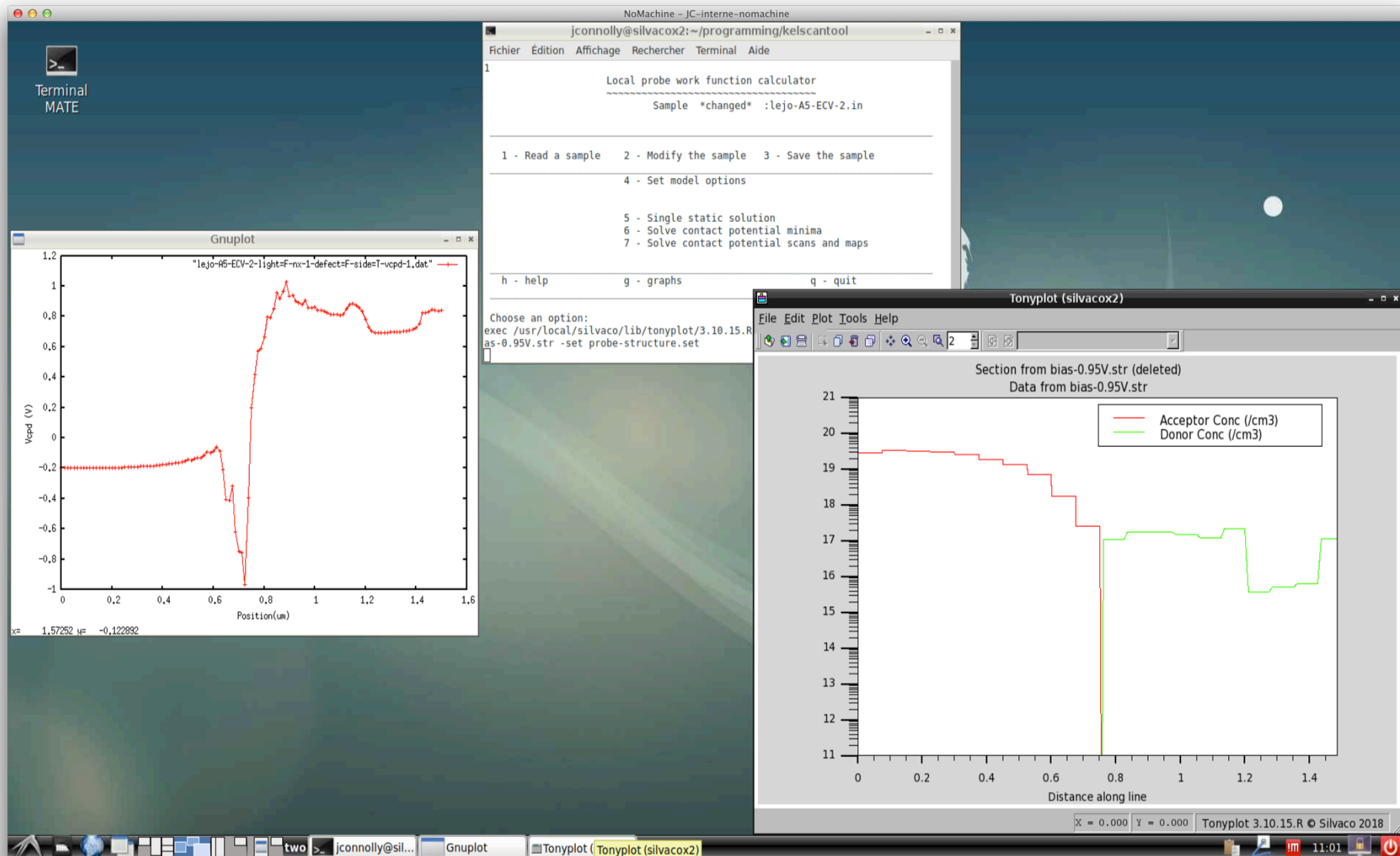
NoMachine - JC-interne-nomachine
jconnolly@silvacox2:~/programming/kelscantool
Fichier Edition Affichage Rechercher Terminal Aide

1 - Scan the overall solution as a function of applied bias (fields)
2 - Scan the contact potential over the surface (Vcpd)
3 - Scan the contact potential as a function of a range of parameters (Vcpd)
4 - Scan integrated field scan in the sample bulk
5 - Scan integrated field scan between sample and probe
q - quit
h - help g - switch graphs on (use with care).
2
(Default 0.000 ) Low position (um)?
(Default 1.500 ) High position (um)?
(Default 1.000 ) Spatial resolution ? (1 = maximum, 120=minimum)
Range 0.000 to 1.500 every 1 grid steps.
Continue ?
y

```

# Kelscan demonstration

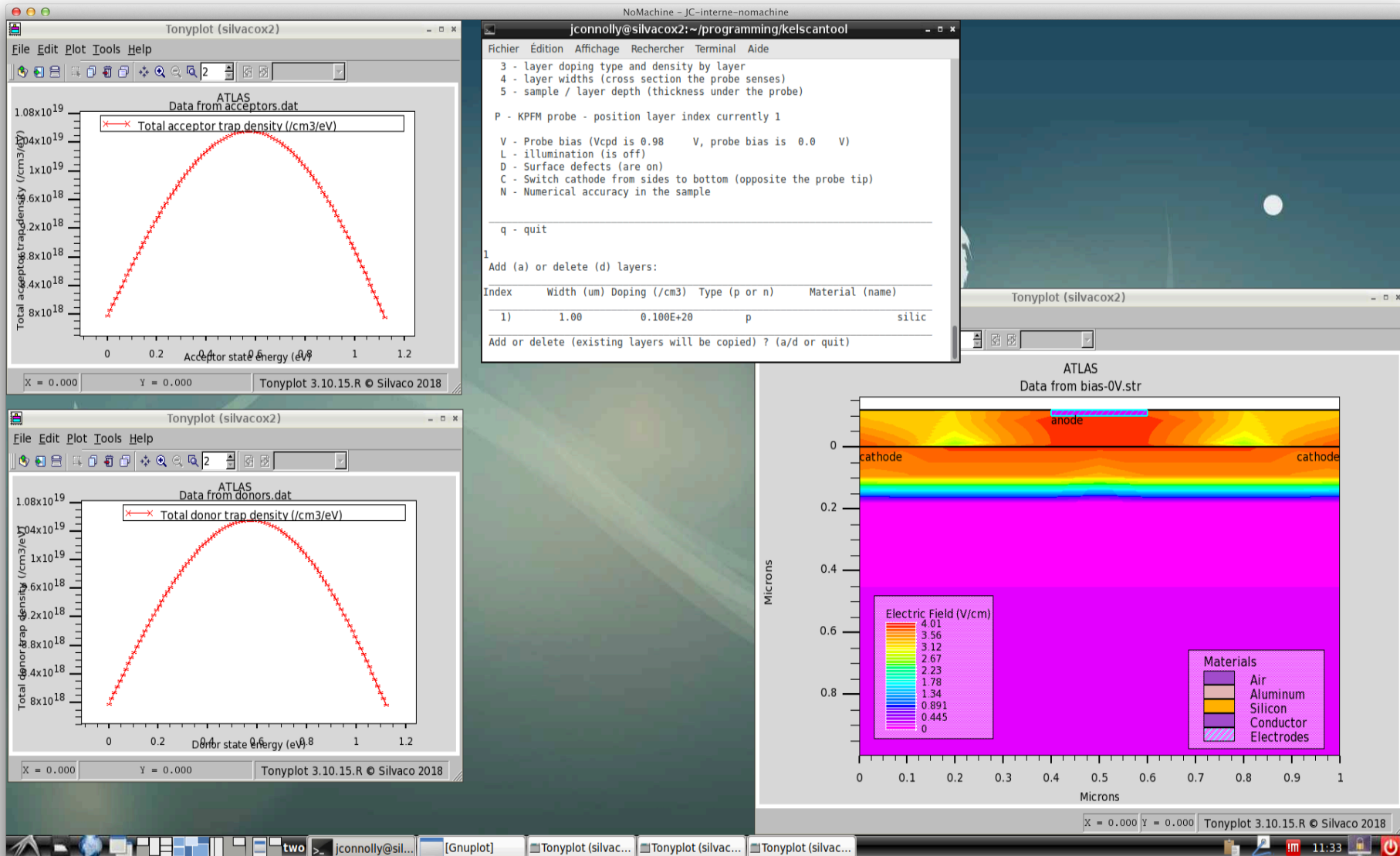
## Contact potential scan : comparison with doping





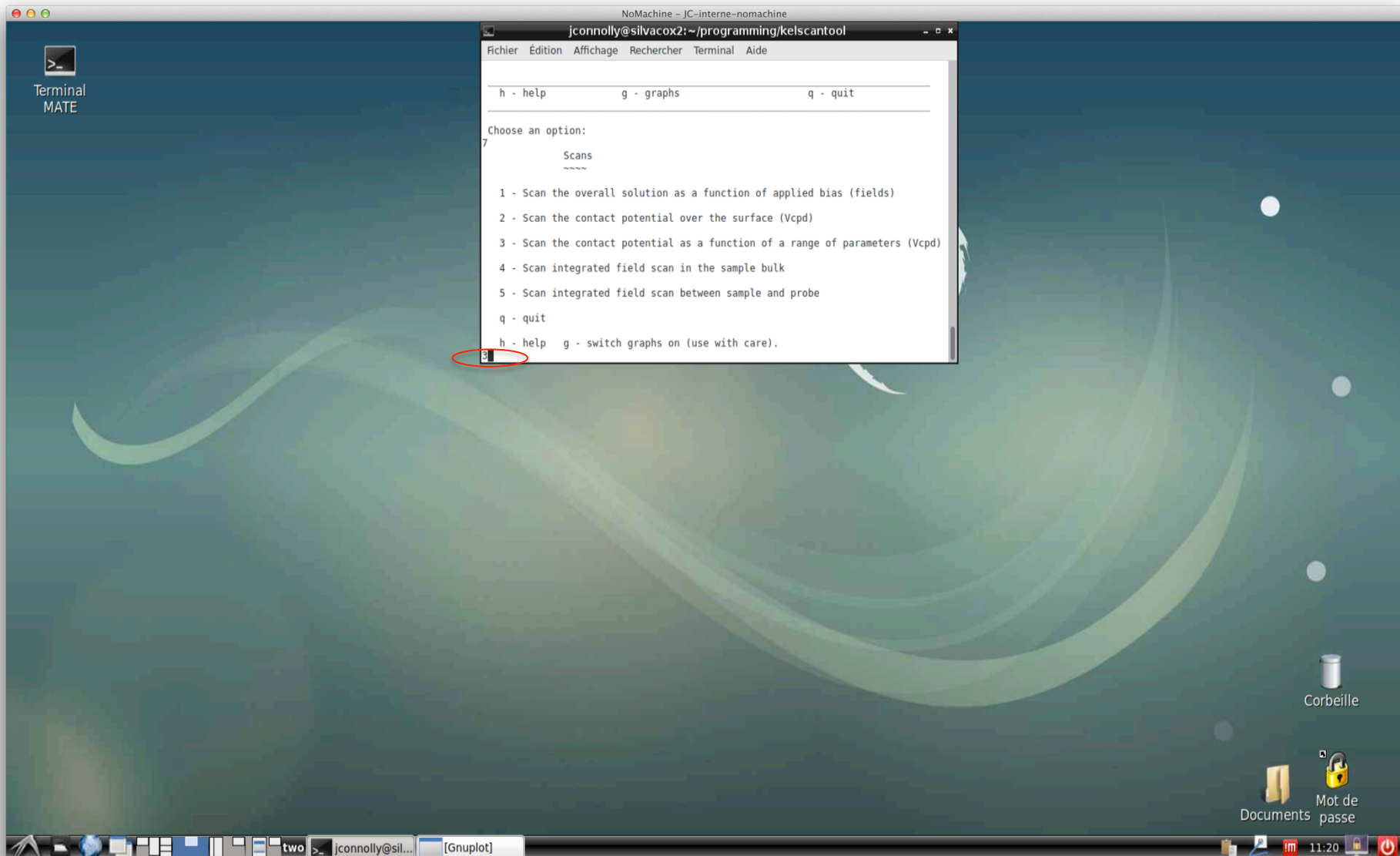
# Kelscan demonstration

Parameter scans : simple single layer homogeneous p-type Si



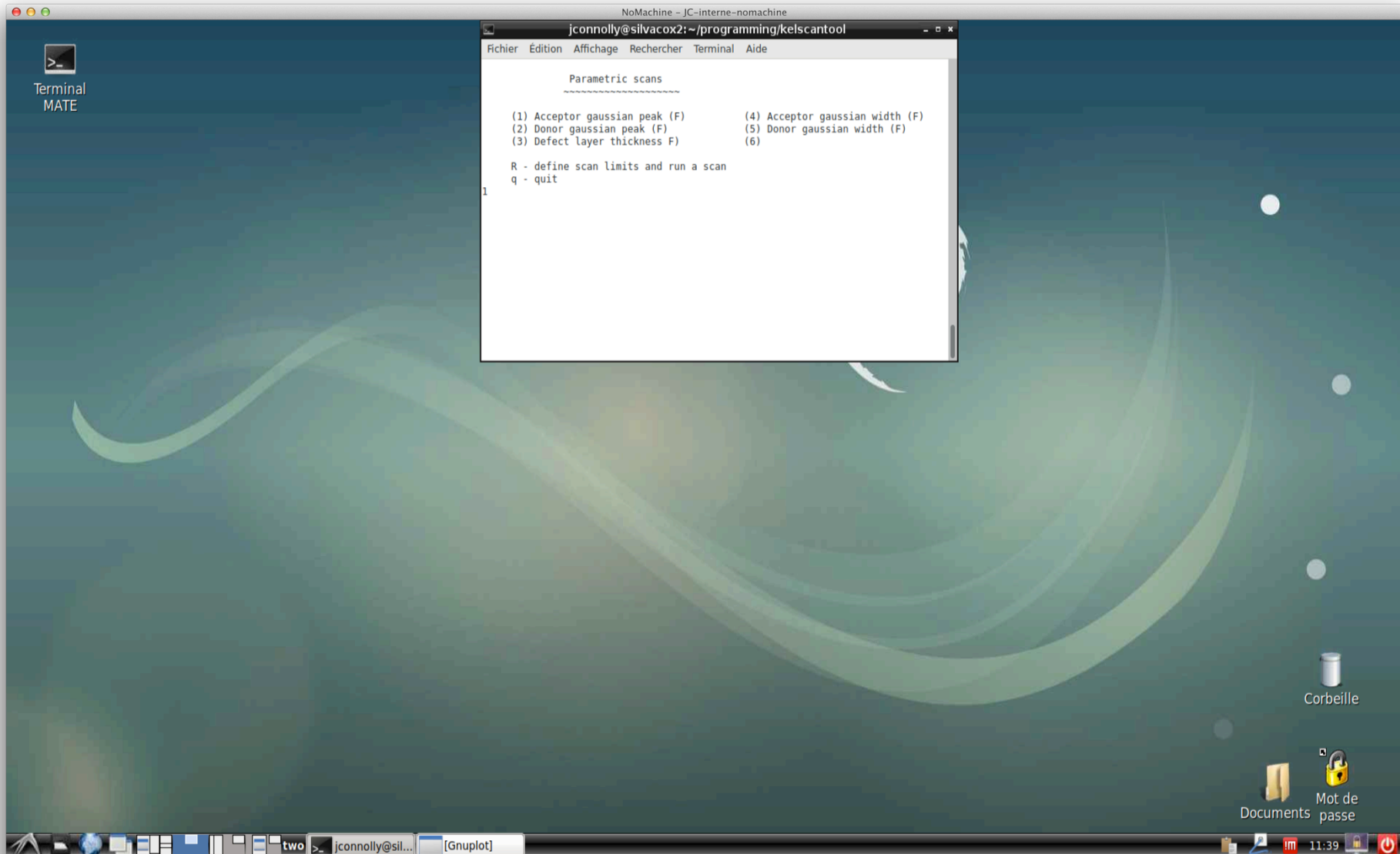
# Kelscan demonstration

## Scanning option 3 : Vcpd scans for a range of parameters



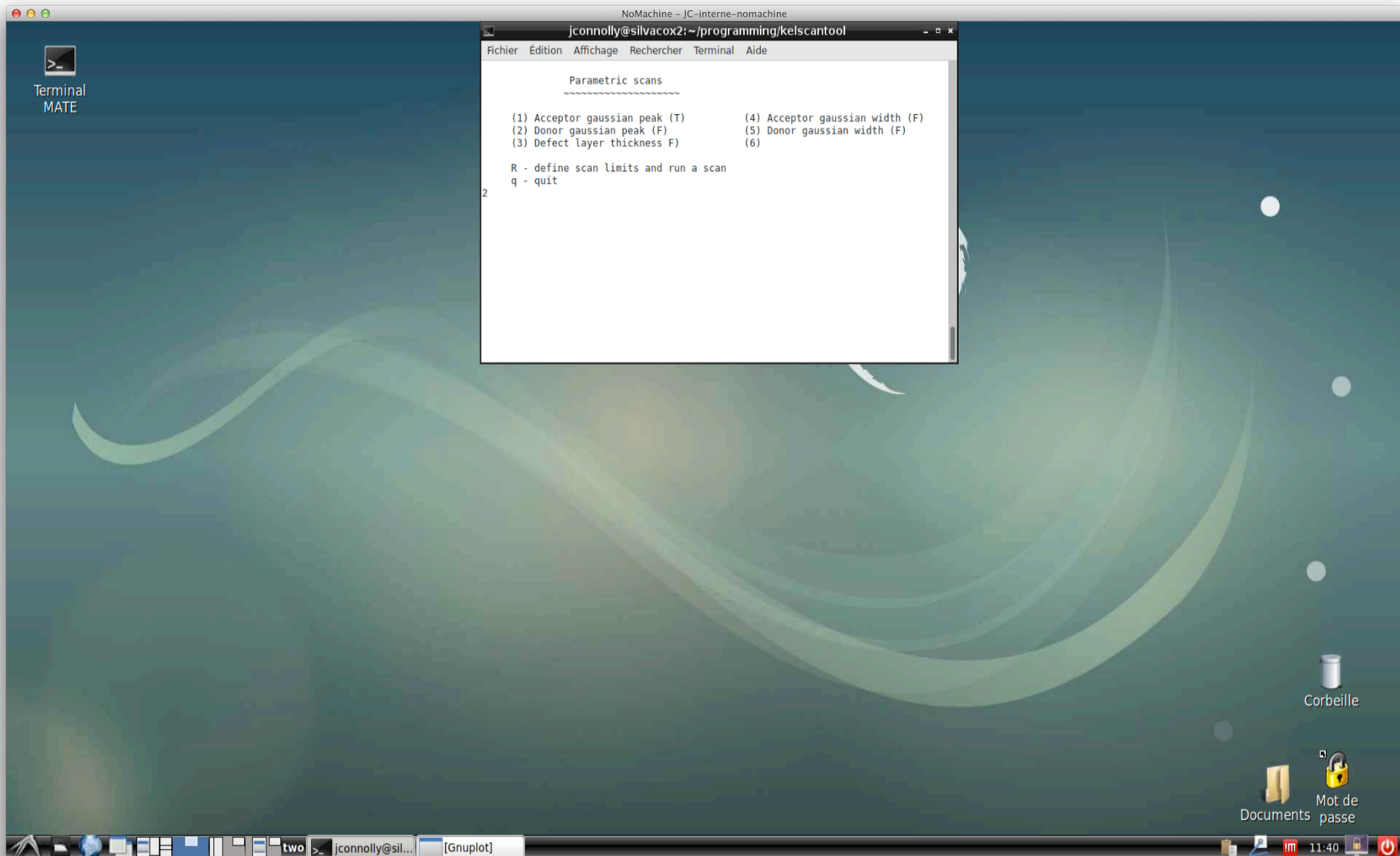
# Kelscan demonstration

2D scan example : First variable, acceptor defect peak density scan



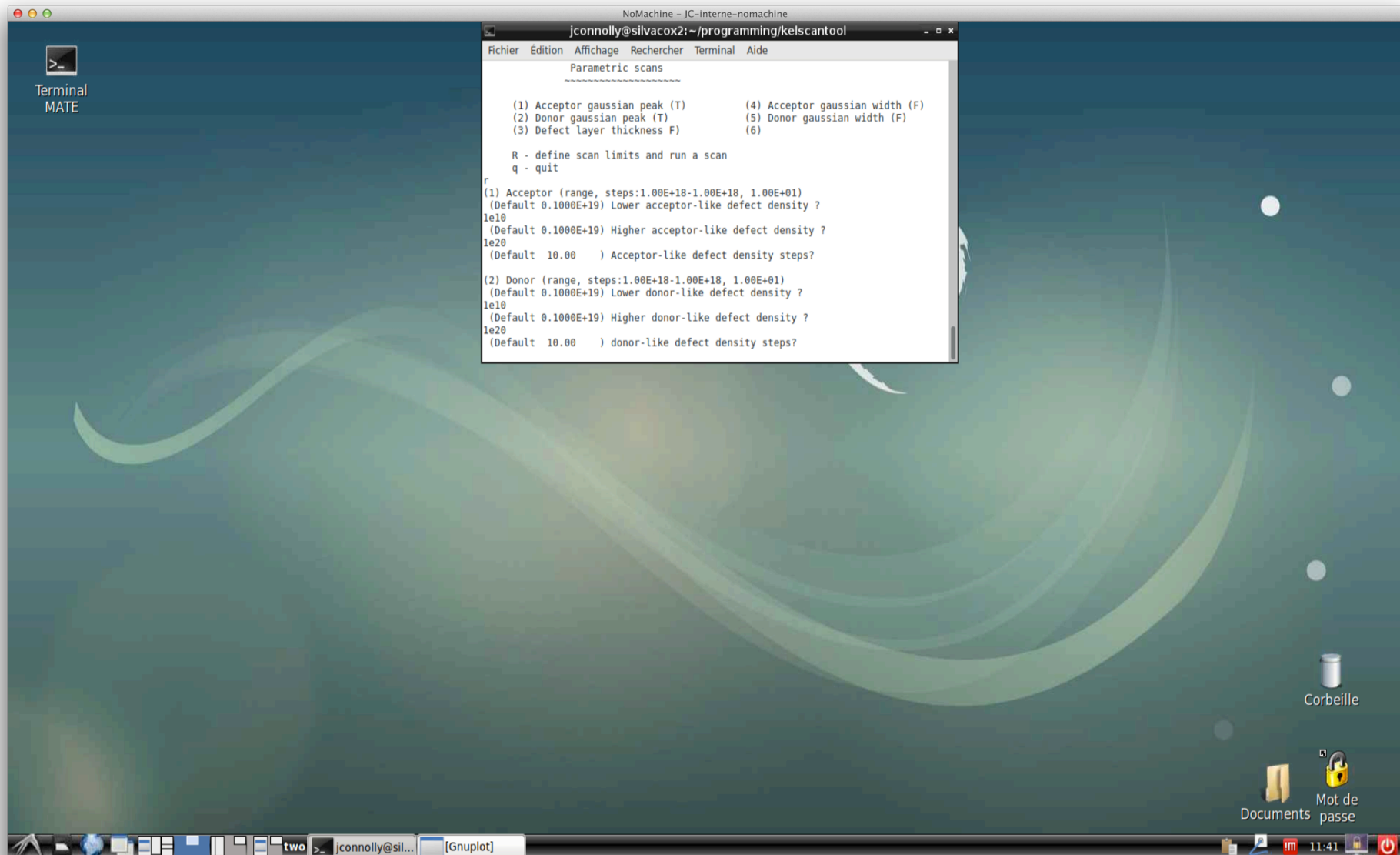
# Kelscan demonstration

2D scan example : Second variable, donor defect peak density scan



# Kelscan demonstration

## Run 2D profile



```
Terminal
MATE

NoMachine - JC-interne-nomachine
jconnolly@silvacox2: ~/programming/kelscantool
Fichier  Edition  Affichage  Rechercher  Terminal  Aide

Parametric scans
-----

(1) Acceptor gaussian peak (T)      (4) Acceptor gaussian width (F)
(2) Donor gaussian peak (T)        (5) Donor gaussian width (F)
(3) Defect layer thickness (F)     (6)

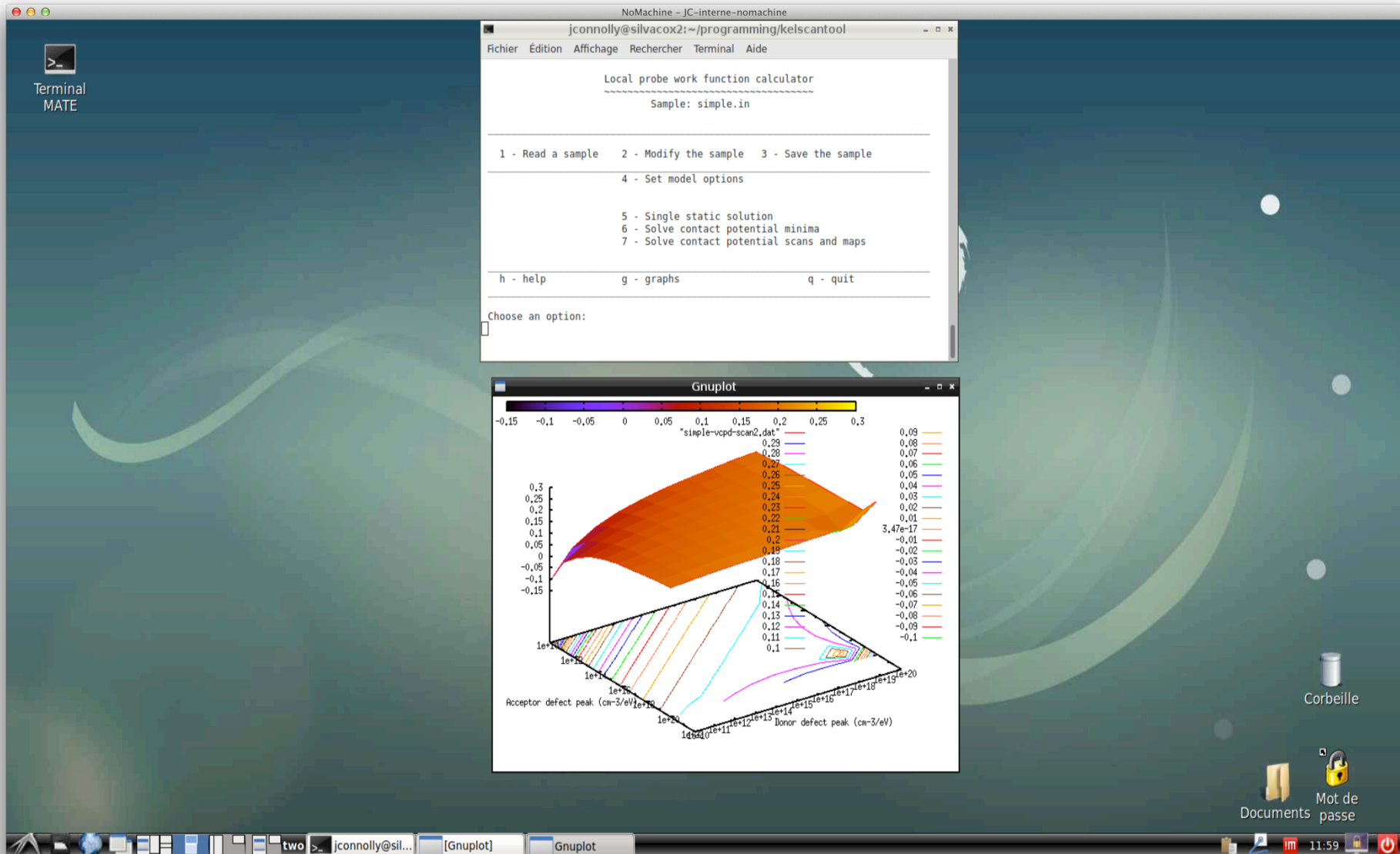
R - define scan limits and run a scan
q - quit

r
(1) Acceptor (range, steps:1.00E+18-1.00E+18, 1.00E+01)
(Default 0.1000E+19) Lower acceptor-like defect density ?
1e10
(Default 0.1000E+19) Higher acceptor-like defect density ?
1e20
(Default 10.00 ) Acceptor-like defect density steps?

(2) Donor (range, steps:1.00E+18-1.00E+18, 1.00E+01)
(Default 0.1000E+19) Lower donor-like defect density ?
1e10
(Default 0.1000E+19) Higher donor-like defect density ?
1e20
(Default 10.00 ) donor-like defect density steps?
```

# Kelscan demonstration

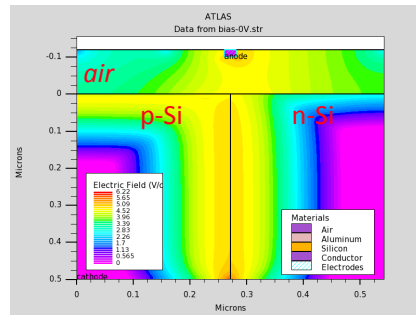
Resulting contact potential map : Data fitting identifies zone consistent with experiment



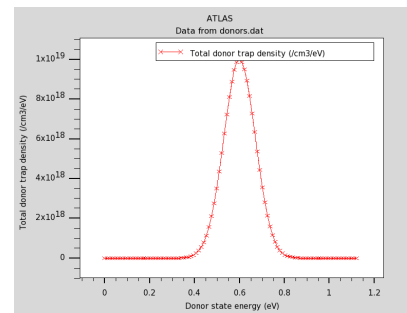
# Surface photovoltage simulations

## Definitions :

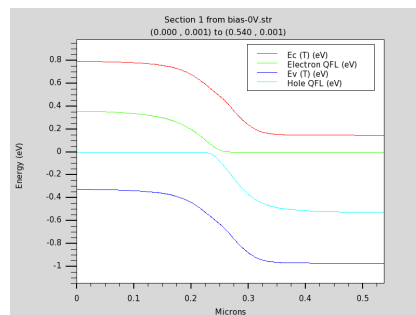
- SPV : The difference in light and dark work functions :  $SPV = \phi(Light) - \phi(Dark)$  independent of tip reference.
- Structure : Symmetric c-Si pn junctions (p-doped layer  $1E17cm^{-3}$   $0.3\mu m$  ; n-doped layer :  $1E17cm^{-3}$   $0.3\mu m$ )



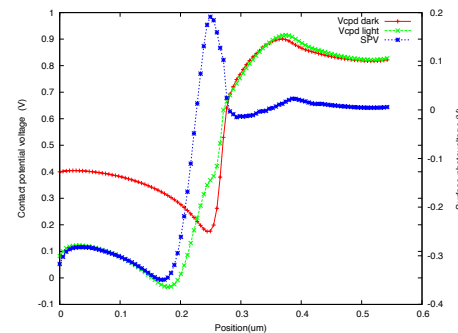
1) pn – surface donor defects  $1e19cm/2$



2) Surface defect donors



3) Surface transverse cut: Bands and populations (light)



4) Surface photovoltage – p side

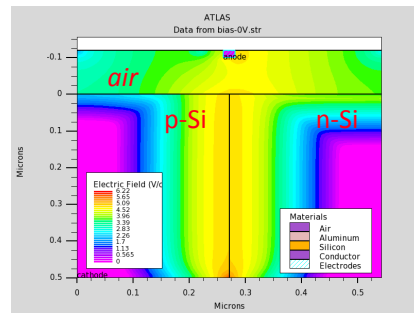
Surface donor defects : • p-side surface depletion and band bending.  
 • n-side close to charge neutral

=> SPV signal on p-side

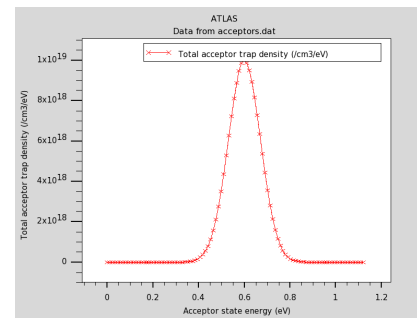
# Surface photovoltage simulations

## Definitions :

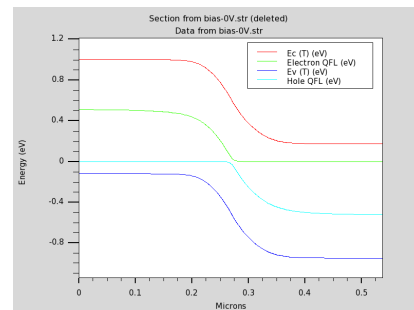
- SPV : The difference in light and dark work functions :  $SPV = \varphi(Light) - \varphi(Dark)$  independent of tip reference.
- Structure : Symmetric c-Si pn junctions (p-doped layer  $1E17cm^{-3}$   $0.3\mu m$  ; n-doped layer :  $1E17cm^{-3}$   $0.3\mu m$ )



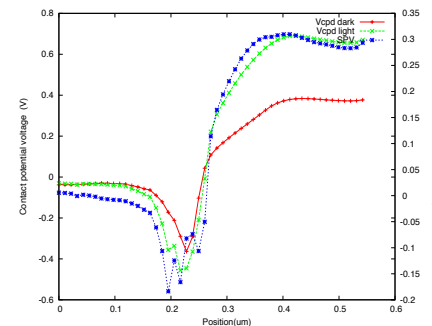
5) pn – surface acceptor defects  $1e19/cm^3$



6) Surface acceptor distribution



7) Surface transverse cut: Bands and populations (light)



8) Surface photovoltage – n side

- Surface acceptor defects :
- p-side surface depletion and band bending.
  - n-side close to charge neutral

=> SPV signal on p-side



## Concluding remarks

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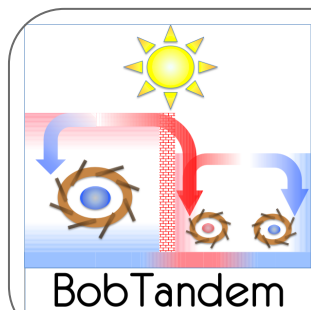
### 1) *Focus of this presentation*

- *Introduction to advanced KPFM techniques*
- *Presentation of user friendly numerical modelling*

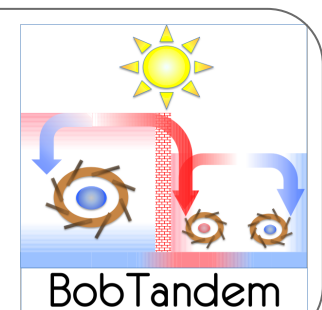
### 2) *Next steps :*

- *Refine description (KPFM tip size for example)*
- *Analyse real materials*

*=> Publication : NanoTexology partner EPJPV*



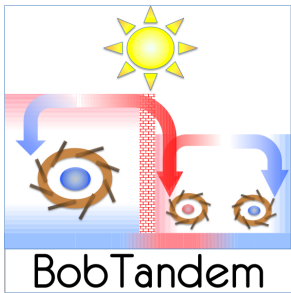
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Project **BOBTandem** - 2019-2022  
<https://bobtandem.wordpress.com>*





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*Thank you for your attention*

