Presented at the COMSOL Conference 2008 Boston

Energy Exchange During Electron Emission from Carbon Nanotubes: Considerations on Tip Cooling Effect and Destruction of the Emitter

Martin Dionne, Jean-Luc Meunier, Sylvain Coulombe
Department of Chemical Engineering, McGill University, 3610 university street,
Montréal (QC), Canada, H3A 2B2, 1-514-398-5566.
mdionnemcgill@gmail.com

McGill

COMSOL
CONFERENCE
BOSTON
2008

Plasma-Québec

Plan

- 1. Introduction
- 2. Theory
- 3. Optimized geometry
- 4. Results and discussion
- 5. Conclusions

McGill

Plasma-Québec

1. Introduction

One important challenge:

Many plasma-based processes may become cost-effective if the power of the discharge could be increased.

Our objectives:

Avoid the melting of the cathode by optimizing the distribution of the current on the surface.

Maximize the accesible <J>.

For arc discharges:

$$J \approx 10^{9-10} \quad A/m^2$$

↓

High temperature

↓

Local melting

↓

Strong erosion at high power

McGill

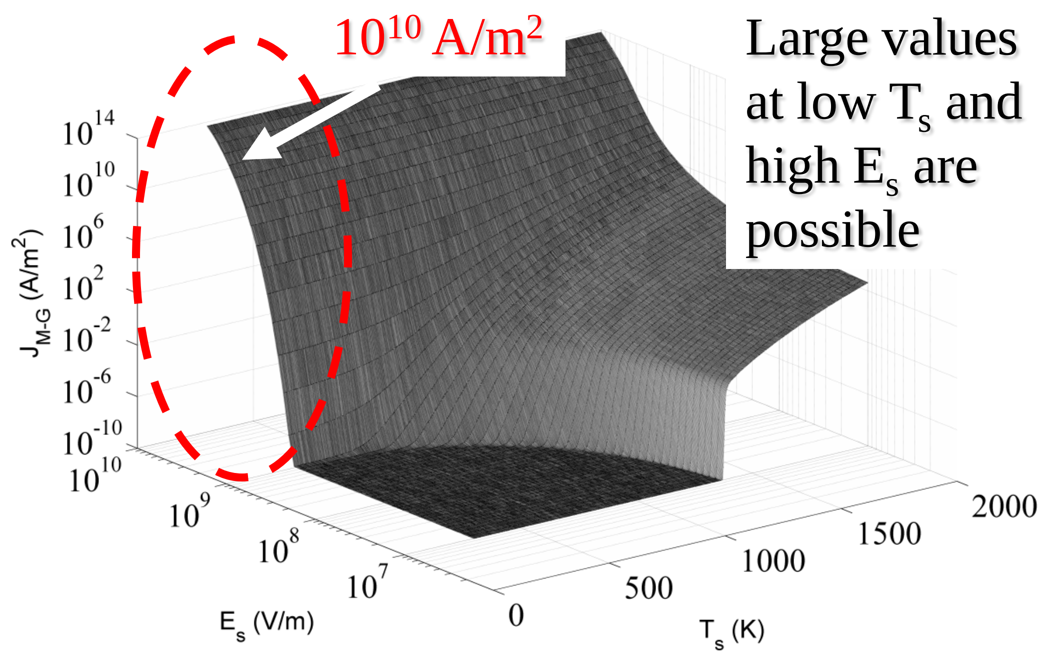
Plasma-Québec

2. Theory: electron emission

- Electron emission

E_s T_s

Murphy and Good theory (M-G)



10^{10} A/m^2

Large values at low T_s and high E_s are possible

- 2 simplifications:
- Fowler-Nordheim (field effect)
- Richardson-Dushman (temperature-driven)

Limited validity:

For significant E_s and T_s only M-G theory applies.

McGill

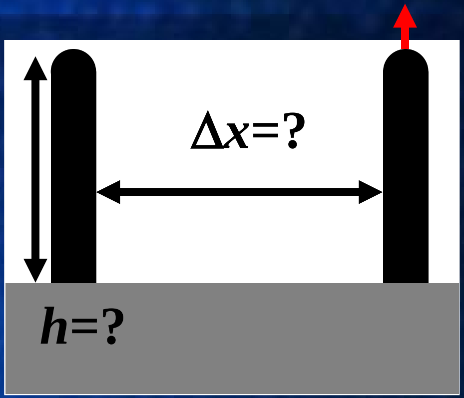
Plasma-Québec

3. Optimized geometry

Tip effect:

The surface field E_s is enhanced at the CNT tips.

β=field enhancement factor



Stronger field

$$E_s \rangle \left(\Delta V / d\right)$$

$(\Delta V/d)$= *applied field*

$$\beta = \frac{E_s}{\Delta V / d}$$

Isolated CNT →

$$\beta = 1.2\left(2.15 + \frac{h}{r}\right)^{0.9}$$

Array → β decreases with the spacing Δx. → $\Delta x_{\text{optimal}}$ α *h*

$\beta \rangle\rangle\rangle 1$ → Enhanced field emission at low ΔV.

$\left(h/r\right) \rangle\rangle\rangle 1$ → If *h* increases, $\Delta x_{\text{optimal}}$ (m) is larger.

For β>>>1: Less emitters per m^2.

McGill

Plasma-Québec

4. Results: electron emission and energy conservation

Electrons can occupy higher energy states at higher T_s.

Cooling >> Heating?

Cooling << Heating?

Replacing electrons all come with $\varepsilon = \varepsilon_F$.

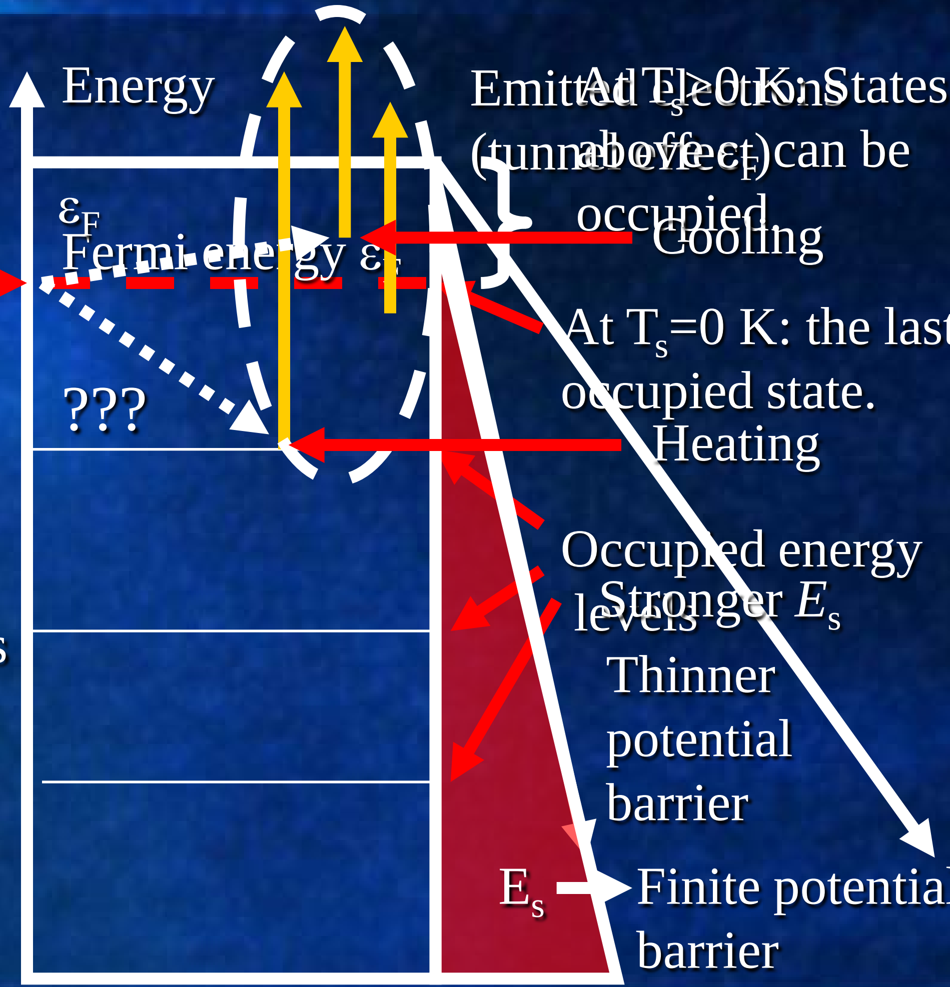
Strong E_s → Electrons are emitted from $\varepsilon < \varepsilon_F$ states too.

High T_s → Many candidates on $\varepsilon > \varepsilon_F$ states.

The energy balance:

<Energy>-Fermi Energy

=The Nottingham effect



Emitted electrons (tunnel effect)

At $T_s > 0$ K: States above ε_F can be occupied.

Cooling

At $T_s = 0$ K: the last occupied state.

Heating

Occupied energy levels

Stronger E_s

Thinner potential barrier

Finite potential barrier

4. Results: the Nottingham effect

- M-G theory:
  - Complex nonlinear expressions.
  - Elliptic integrals.
  - Requires numerical integration.

$$\infty$$

$$\varepsilon_{Not} = \frac{e}{J_{M-G}} \int_{-\infty}^{\infty} (\ldots) dE + \phi_0$$

Typical situation:

$\varepsilon_{Not} \rangle 0$ Cooling

$\varepsilon_{Not} \langle 0$ Heating

ε_{No} $\frac{}{-G}\int_{-\infty}^{\infty}($ $dE + \phi_0$

M-G theory is replaced. Wrong.

- 2 simplifications:
- Fowler-Nordheim (field effect)
- Richardson-Dushman (temperature-driven)

No valid approximation of ε_{Not}

In our source: $\varepsilon_{Not} = 1.5 k_B T$ was assumed (not true).

Average energy of emitted electrons

"-Fermi energy"=work function of the material

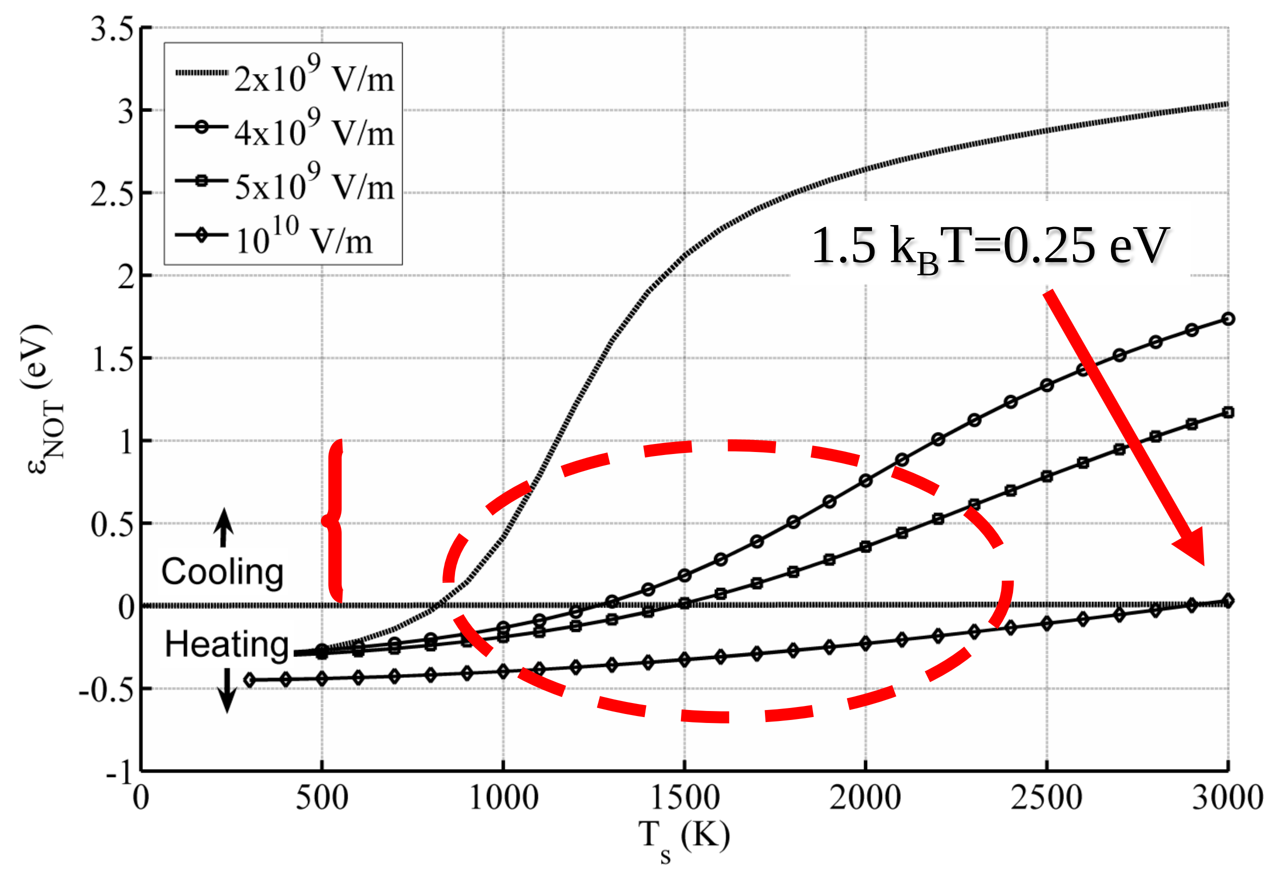
J: too small by about 10^2.

J also too small.

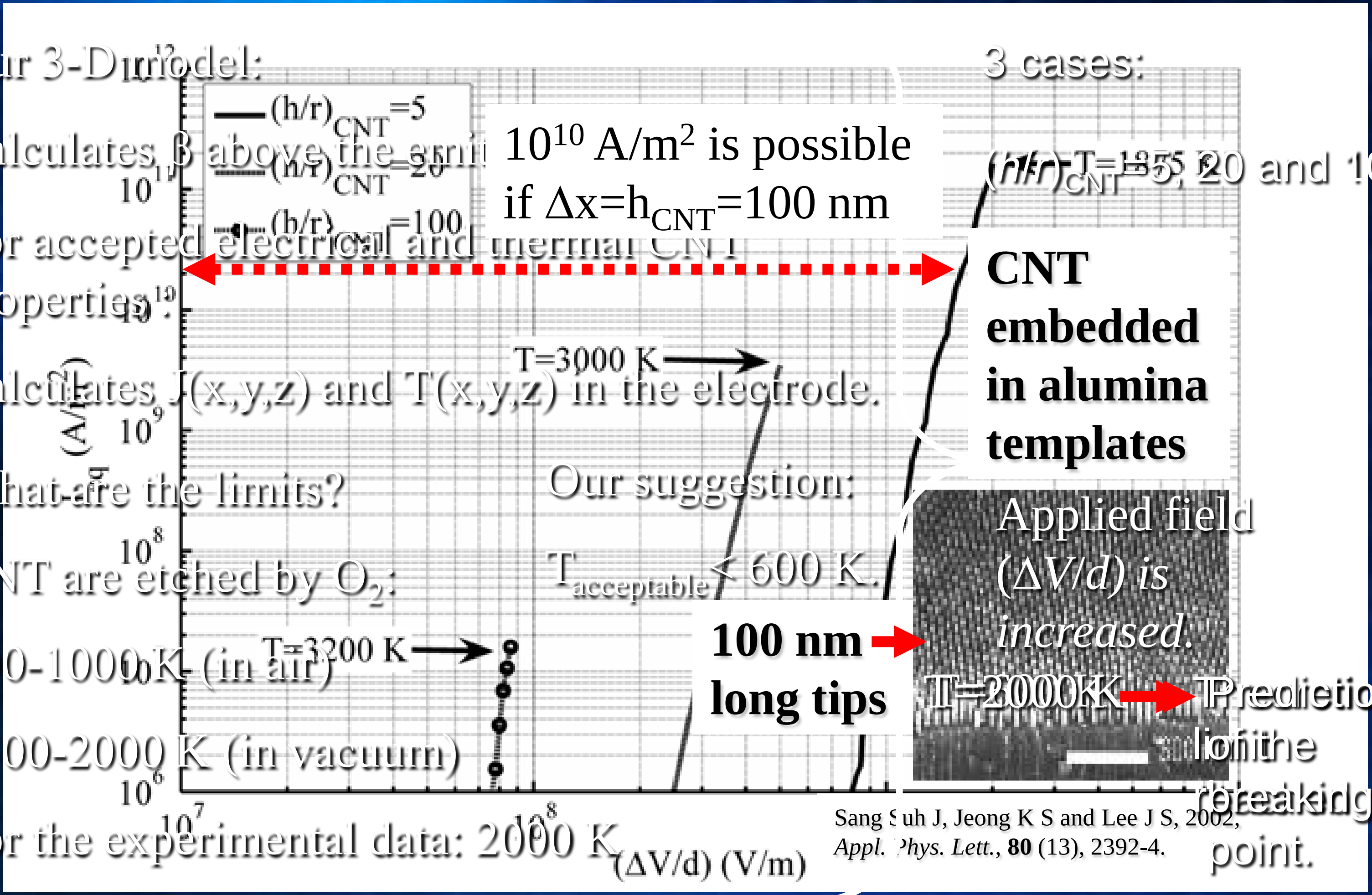
McGill

Plasma-Québec

4. Results: the Nottingham effect



4. Results: theoretical performances



10^{10} A/m² is possible if $\Delta x = h_{CNT} = 100$ nm

CNT embedded in alumina templates

100 nm long tips

Applied field (ΔV/d) is increased.

Sang Suh J, Jeong K S and Lee J S, 2002, *Appl. Phys. Lett.*, **80** (13), 2392-4.

Our 3-D model:

Calculates β above the emit

For accepted electrical and thermal CNT properties:

Calculates J(x,y,z) and T(x,y,z) in the electrode.

What are the limits?

CNT are etched by O_2:

800-1000 K (in air)

1500-2000 K (in vacuum)

For the experimental data: 2000 K

3 cases:

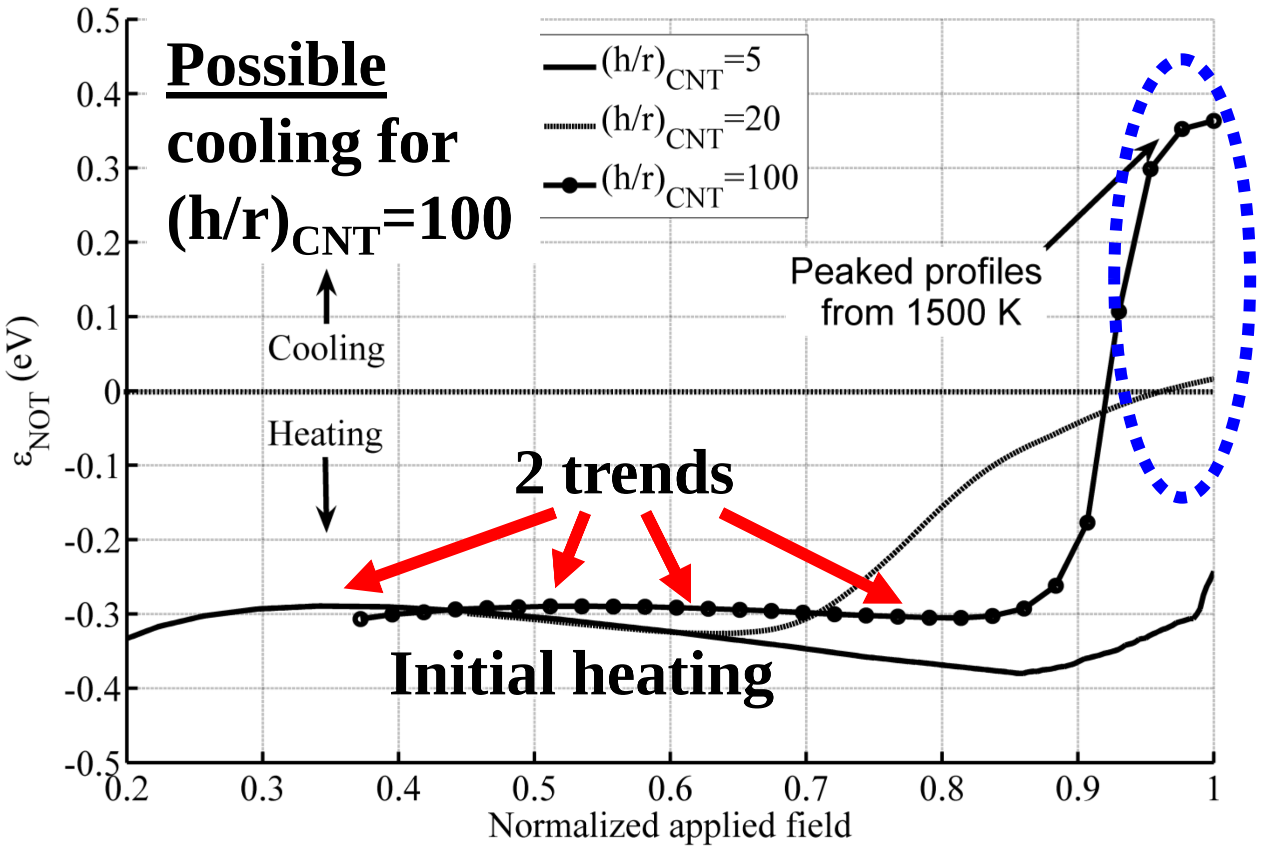
$(h/r)_{CNT}=5$, 20 and 100

Our suggestion:

$T_{acceptable} < 600$ K.

T=2000K → Prediction of the breaking point.

4. Results: evolution of ε_{Not}



Possible cooling for $(h/r)_{CNT}$=100

Peaked profiles from 1500 K

2 trends

Initial heating

4. Results: comparison with experiments

- The destruction mechanism for CNT electron emitters at high current.

Observation 1: accurate predictions of the breaking point location.

Long CNT: a cluster region of the breaking point from the tip.

2: Short CNT are destroyed unexpectedly.

Short CNT: no tip cooling effect, rapid increase of T above 2000 K.

Assumption of thermal

Explanation from the

Unexplained

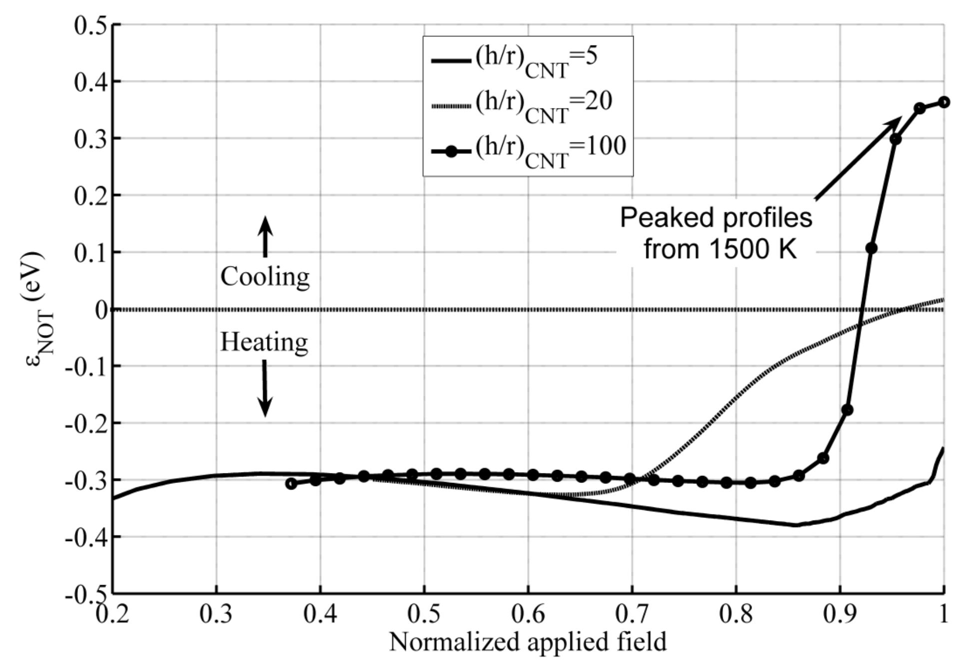
besides Joule effect)

CNT on W microtips, high vacuum.

Long CNT are cooled at their tips.

Short CNT are heated instead and burn sooner than expected.

Wei Wei *et al*, 2007, *Nano Lett*, **7** (1), 64-8.



McGill

Plasma-Québec

5. Conclusions

- A promising theoretical design for strong emission at low temperatures was selected.
- Alumina templates are compatible substrates for the best geometry.
- The Nottingham effect plays an important role in the destruction of CNT electron emitters.
- Our model explains the different trends for the destruction of long and short CNT during electron emission.

Acknowledgements

- COMSOL
- McGill Plasma Group
- Department of Chemical Engineering technical personnel.
- Funding:
  - Plasma-Québec
  - CRSNG - Discovery and Canada Research Chair programs
  - FQRNT – Team project
  - McGill University

McGill

Plasma-Québec