V. So where is the problem?
Causes of non-uniformity.
Some recommendations.

Summary so far: it is reassuring to know that the basic design is ideally and inherently uniform.

Reminder from Section 1: an ideal showerhead reactor has:

• Uniform gas inlet flow, with gas outlet at the perimeter, uniform pressure, and uniform temperature (isothermal reactor).

• Uniform plasma (laterally over the substrate, not across the gap) of charged and neutral radical and gas species

• Instantaneous plasma equilibration on ignition.

This means that any non-uniformity is due to perturbations. We just have to identify where are the departures from the ideal design, and correct them.

A study of the perturbations therefore requires more complex, 3D models.

Consider some perturbations to ideal showerhead reactor:

Imperfect showerhead reactor:

- Pressure drop in direction of flow (non-uniformity proportional to the inverse cube of the electrode gap *H*!)
- Non-uniform input flow - pressure drop along showerbox; partial area showerhead; or with accidental leaks
- Sidewall deposition - supplementary sink for depositing species (lateral exclusion zone ~ electrode gap) **EDGE LOCALIZED**
- Inappropriate pumping configuration

Non-uniform plasma:

- Reactor dimension > 1/10 RF vacuum wavelength (standing wave)
- Asymmetric electrodes, eg. grounded sidewalls (telegraph effect) **EDGE LOCALIZED**
- Edge localized modes due to discontinuities in permittivity and geometry: fringing fields **EDGE LOCALIZED**
- (probably not the skin effect, because the skin depth > plasma thickness for depostion conditions)
- Arcs and hollow cathodes in gaps of the reactor, showerhead, pumping grid, & power-feed - non-uniform RF current distribution
- Dust particles suspended in non-uniform clouds (negative ion trapping, polymerisation, colloidal plasma) **(EDGE LOCALIZED)**
- Thermophoresis of particles in non-isothermal reactor (thermal radiation; high-density plasma heating of dielectric substrate)

Slow equilibration; long time to steady state:

- Open reactor with dead volume and indirect pumping at vacuum chamber walls

Miscellaneous:

- Gaps or holes in electrode behind the substrate - perturbed RF capacitive coupling
- Substrate edges - physical step (non-uniform gap), dielectric step (E-field distortion, powder trap) **EDGE LOCALIZED**

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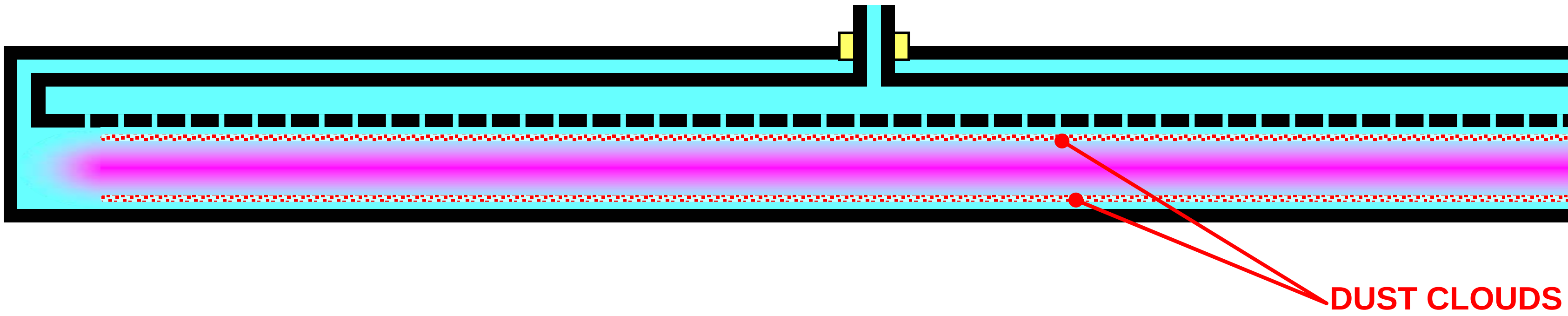
Sources of non uniformity
DUST CLOUD?



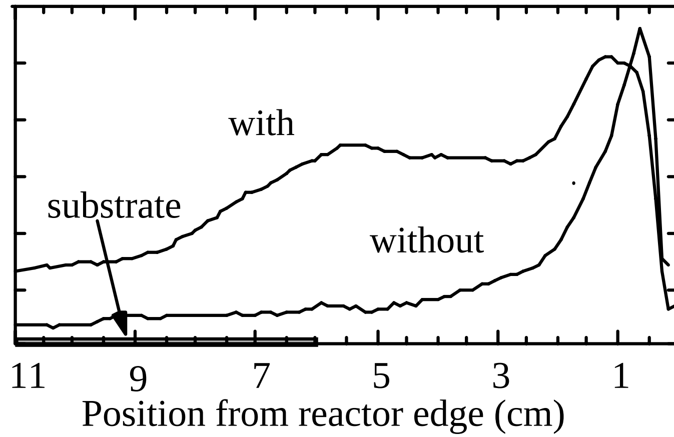
For a-Si:H deposition (amorphous Silicon), uniformity is mostly ruled by the dust cloud uniformity. Most important is Temperature uniformity. Indeed thermophoresis would push the dust cloud towards the cold side

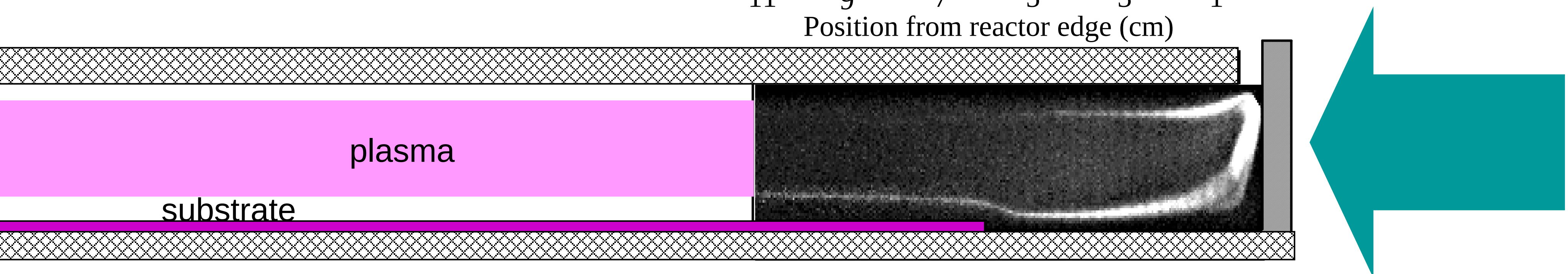
isothermal reactors:

$\Delta T_{glass} < +/- 2\ °C$

$\Delta T_{walls} < +/- 5\ °C$

Powder trapping at reactor edge: shallow potential traps due to junction with substrate





90 degree Mie scattering of a laser sheet

Ch. Hollenstein, A. A. Howling, C. Courteille, J.-L. Dorier, L. Sansonnens, D. Magni and H. Müller, Amorphous and Microcrystalline Silicon Technology MRS Symp. Proc., **507** 547-557 (1998).

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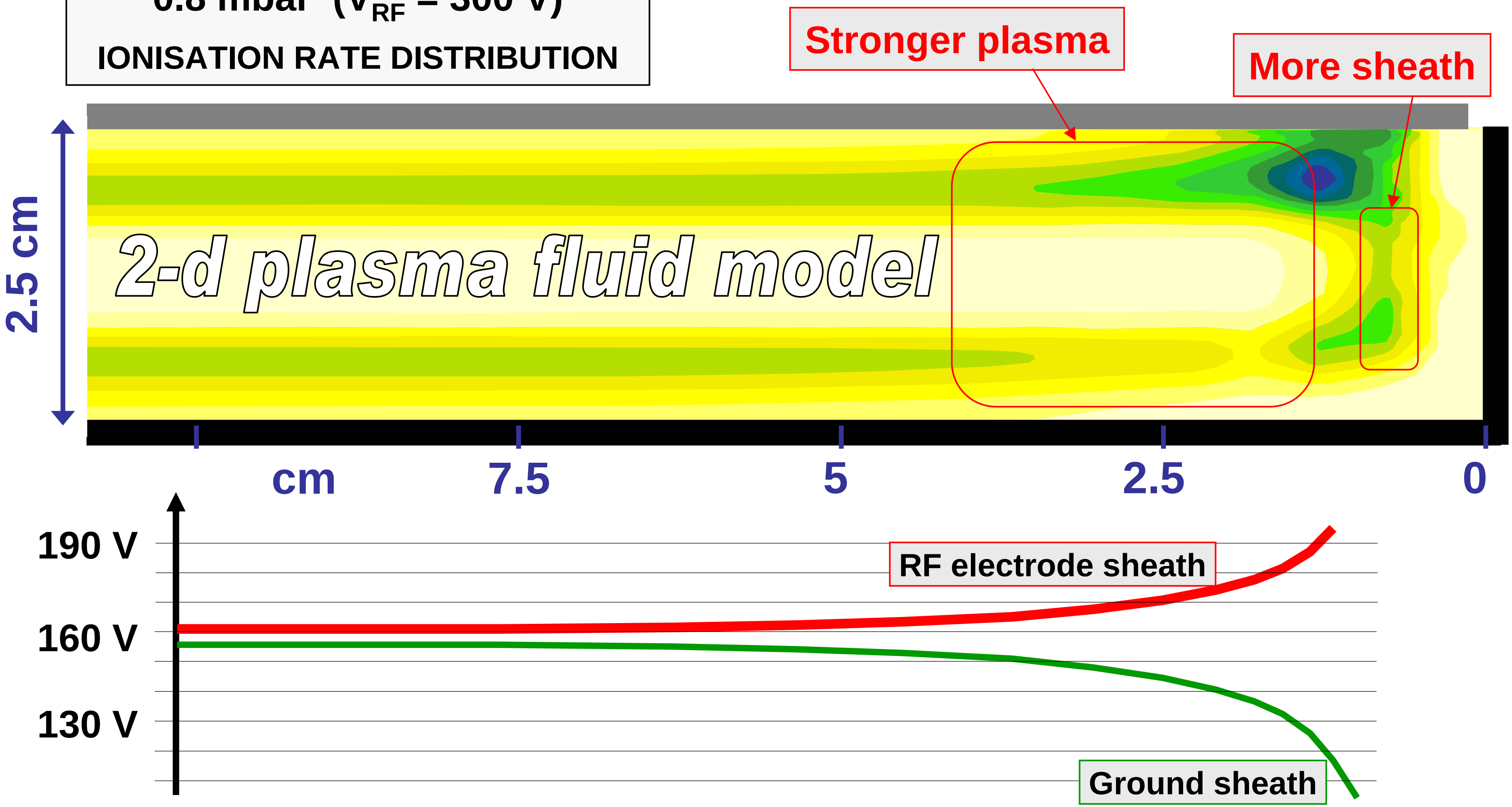
Non-uniform edge plasma

Hydrogen plasma
0.8 mbar (V_{RF} = 300 V)
IONISATION RATE DISTRIBUTION



J. Schmitt, M. Elyaakoubi, and L. Sansonnens,
Plasma Sources Sci. Technol. **11**, A206 (2002)

Non-uniformity is often an **EDGE LOCALIZED** effect.

There is a non-uniform "edge exclusion zone" of several cm, whether the reactor is 13 cm diameter or 300 cm diagonal.

The bad uniformity zone does not necessarily scale down with smaller reactor size.

Therefore a laboratory reactor can be dominated by non-uniformity zone.

Crux of the problem for upscaling of small reactors:

- The process parameters which give the desired device in the lab reactor may not give the same plasma conditions in a large area reactor because the lab device was exposed to the *non-uniform* conditions corresponding to those process parameters.
- When external dead volume is used for diagnostic access in lab reactors, the long equilibration time means that the real process parameters may not correspond to the intended steady-state design conditions.

The problem is not necessarily with the upscaled reactor; the problem is with misinterpreted process parameters from the non-uniform *small* reactor.

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Summary of recommendations for large-area reactor design

- Showerhead reactor, directly pumped, closed electrodes (no dead volume)
- 'Uniform pressure' (flow not too high, pressure not too low, electrode gap not too small)
- Uniform RF voltage (special precautions necessary if size > RF vacuum wavelength/10)
- Symmetric electrodes, and avoid edge fringing fields
- Isothermal
- Avoid trapping of non-uniform dust clouds
- Avoid sidewalls (eg cylindrical reactor)
- Continuous dielectric surface for the substrate electrode (physically & electrically invisible)
- Unstable plasmas (eg some types of electronegative gas) will be nonuniform even in perfect reactors
- Monitor intensive parameters such as depletion, RF electrode voltage, optical emission

Keep it simple: avoid complex configurations for gas flow and electric field.

No surprise: for uniform deposition, need a laterally-uniform reactor!

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