FROM RESEARCH TO INDUSTRY

MODELLING OF DYNAMICS LEADING TO TRANSIENT BOILING CRISIS IN A HELIUM NATURAL CIRCULATION LOOP

H. Furci, B. Baudouy

Service d'Accélérateurs, Cryogénie et Magnétisme

IRFU, DSM

CEA de Saclay

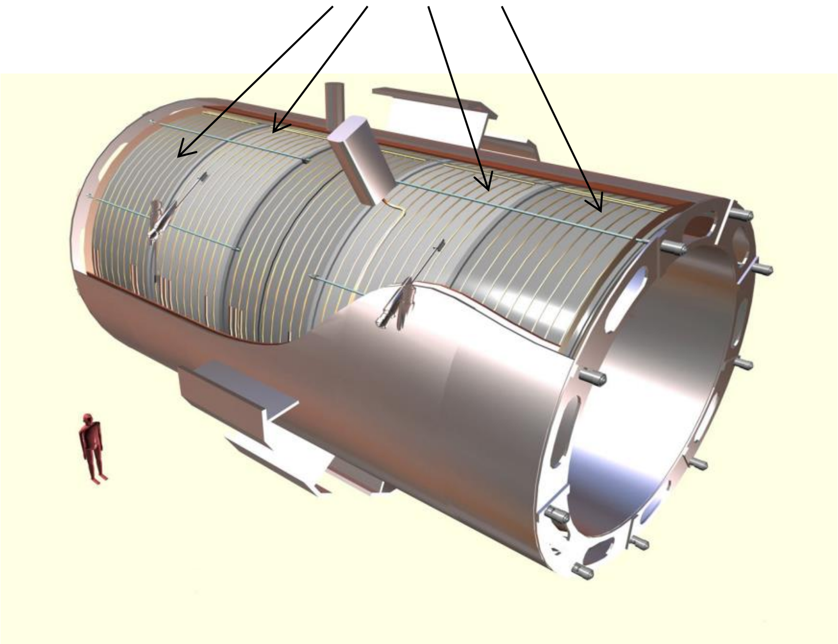
CHATS-AS 2015

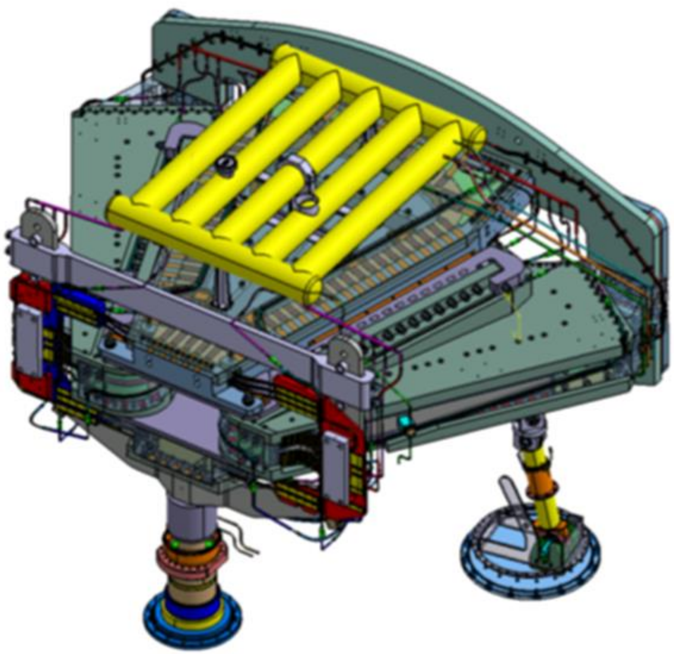
SEPTEMBER 14TH TO 16TH 2015, BOLOGNA, ITALIA

MOTIVATION AND OBJECTIVES

- **Helium natural convection** is a cooling scheme in large **superconducting magnets**
  - CMS at the LHC for CERN
  - R3B-GLAD for GSI
  - Passive safety reasons
  - Already studied in steady state
  - Not thoroughly studied in transients

CMS thermosiphon cooling pipes

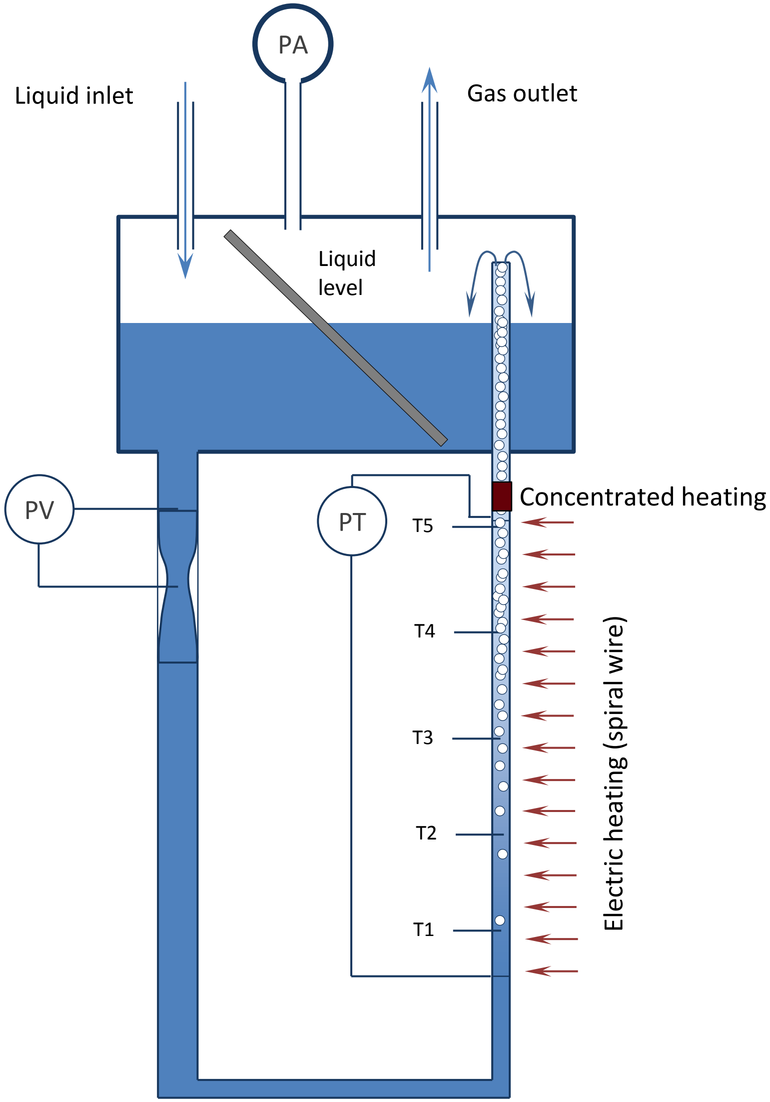


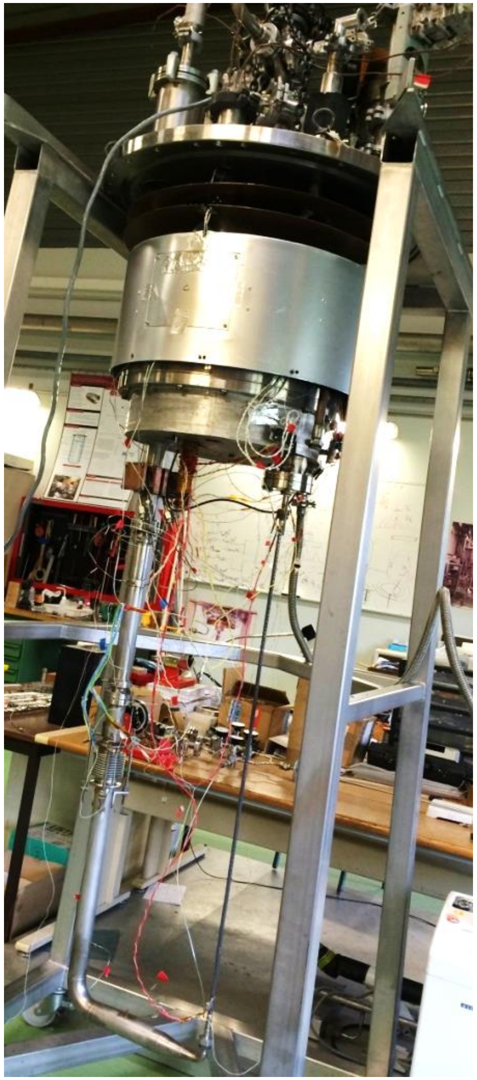


R3B-GLAD Cooling System

- We conducted **experiments** on a helium natural circulation facility
  - To **explore the existing boiling regimes** during transients at different powers and positions of a heated section;
  - To identify **heat transfer deterioration** phenomena and ways of **mitigating its effects**.
- We modeled the helium natural circulation loop
  - To **understand and predict** the observed phenomena

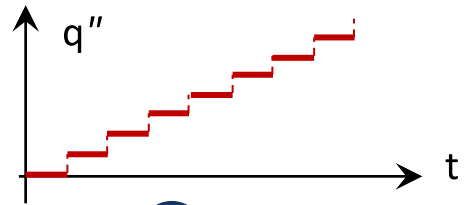
EXPERIMENTAL SET-UP

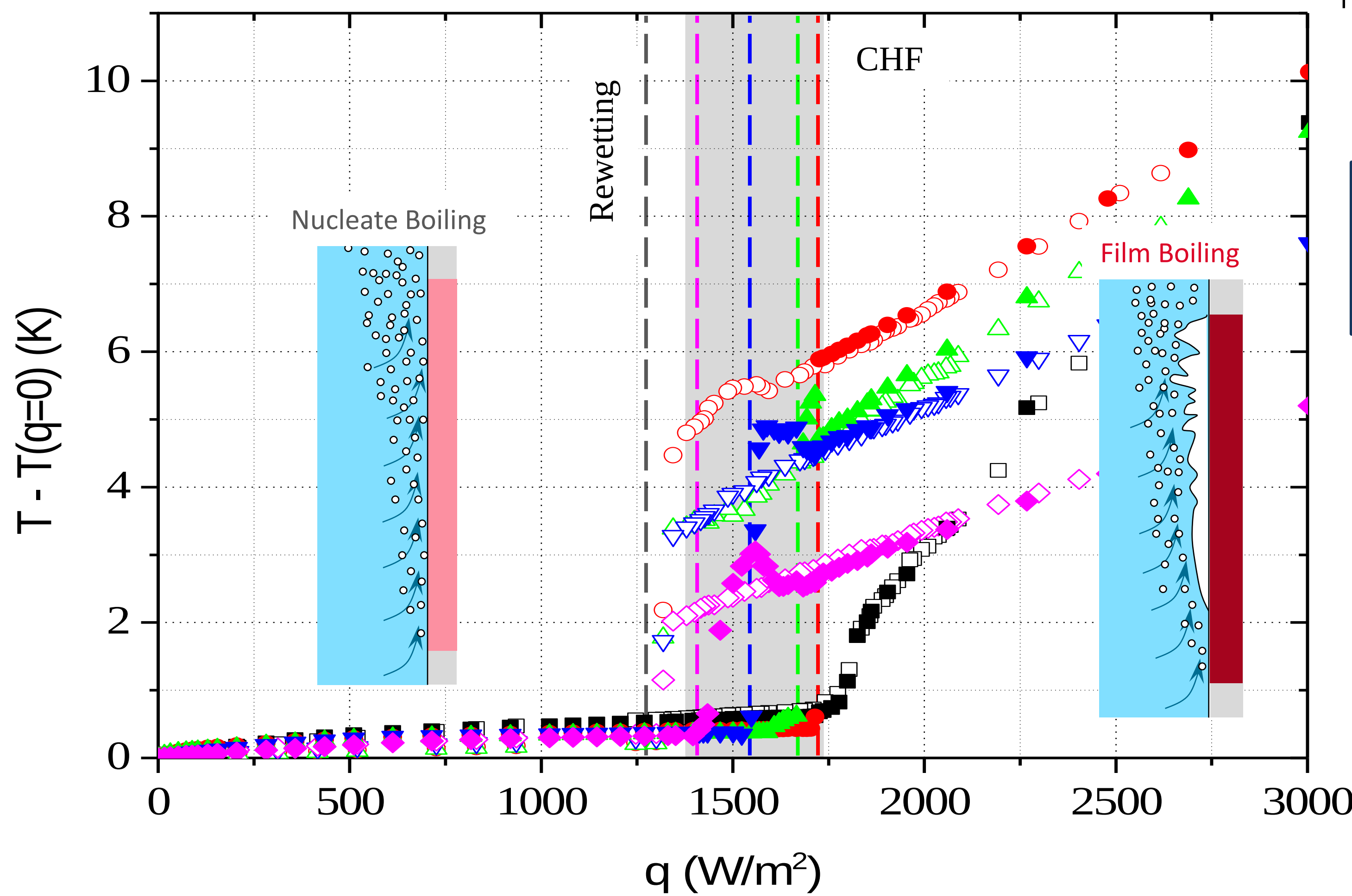


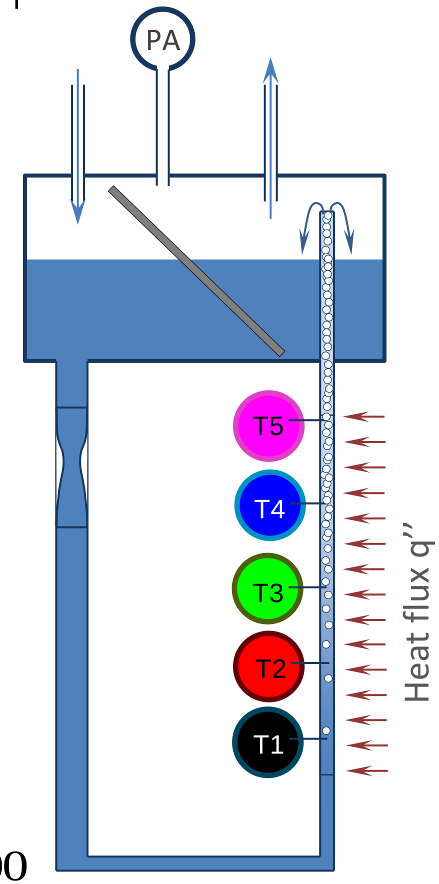


STEADY-STATE BOILING REGIMES

Power is increased **gradually** (quasi-steady state)
Two boiling regimes take place depending on power (and position).

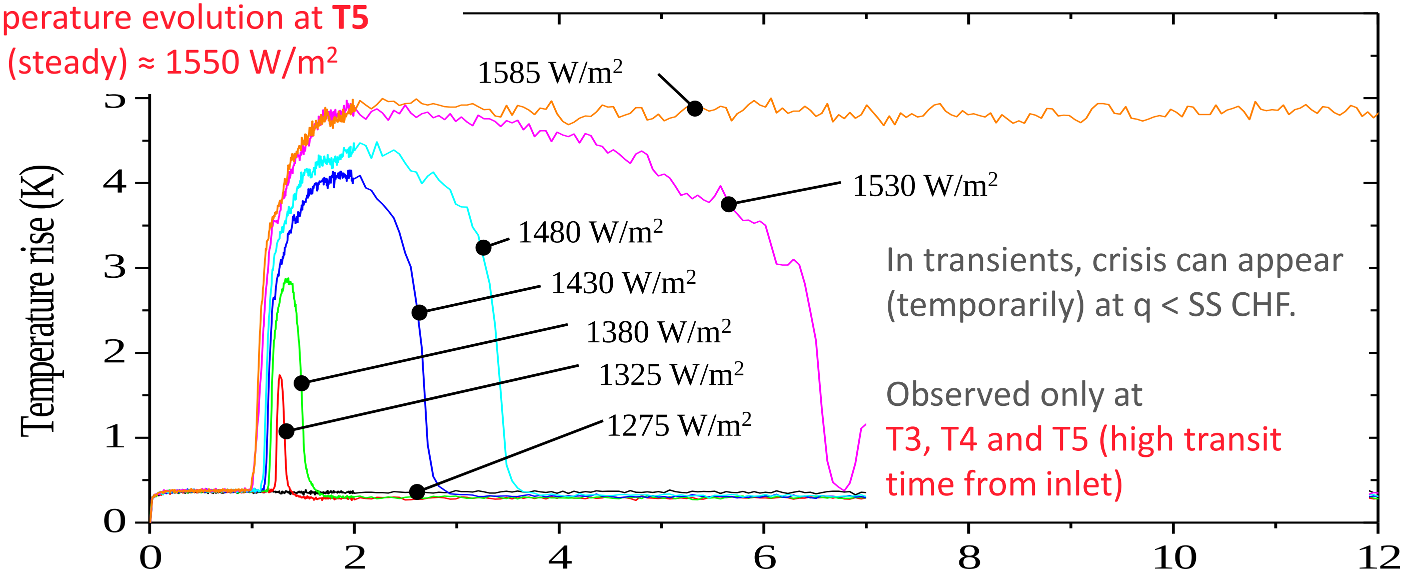


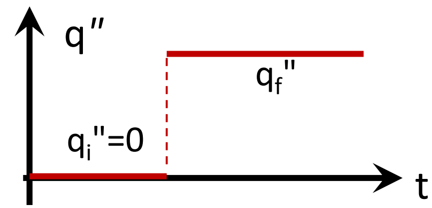




EXPERIMENTAL RESULTS ON TRANSIENT CRISIS

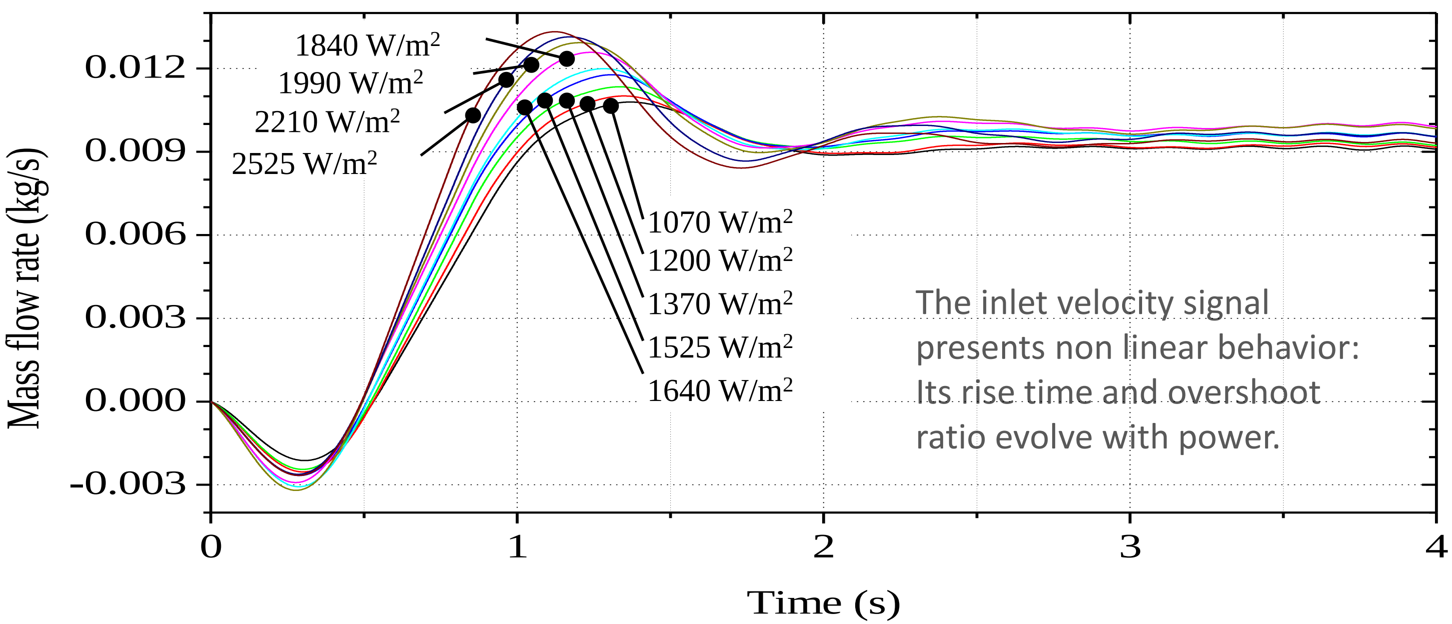
Temperature evolution at **T5**
CHF (steady) ≈ 1550 W/m²



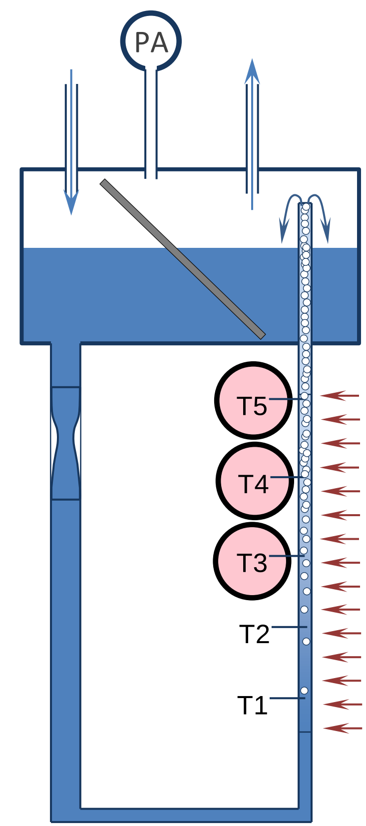


In transients, crisis can appear (temporarily) at q < SS CHF.

Observed only at T3, T4 and T5 (high transit time from inlet)



The inlet velocity signal presents non linear behavior: Its rise time and overshoot ratio evolve with power.

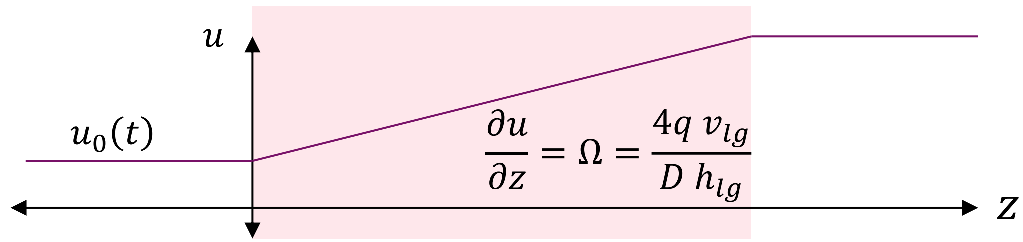


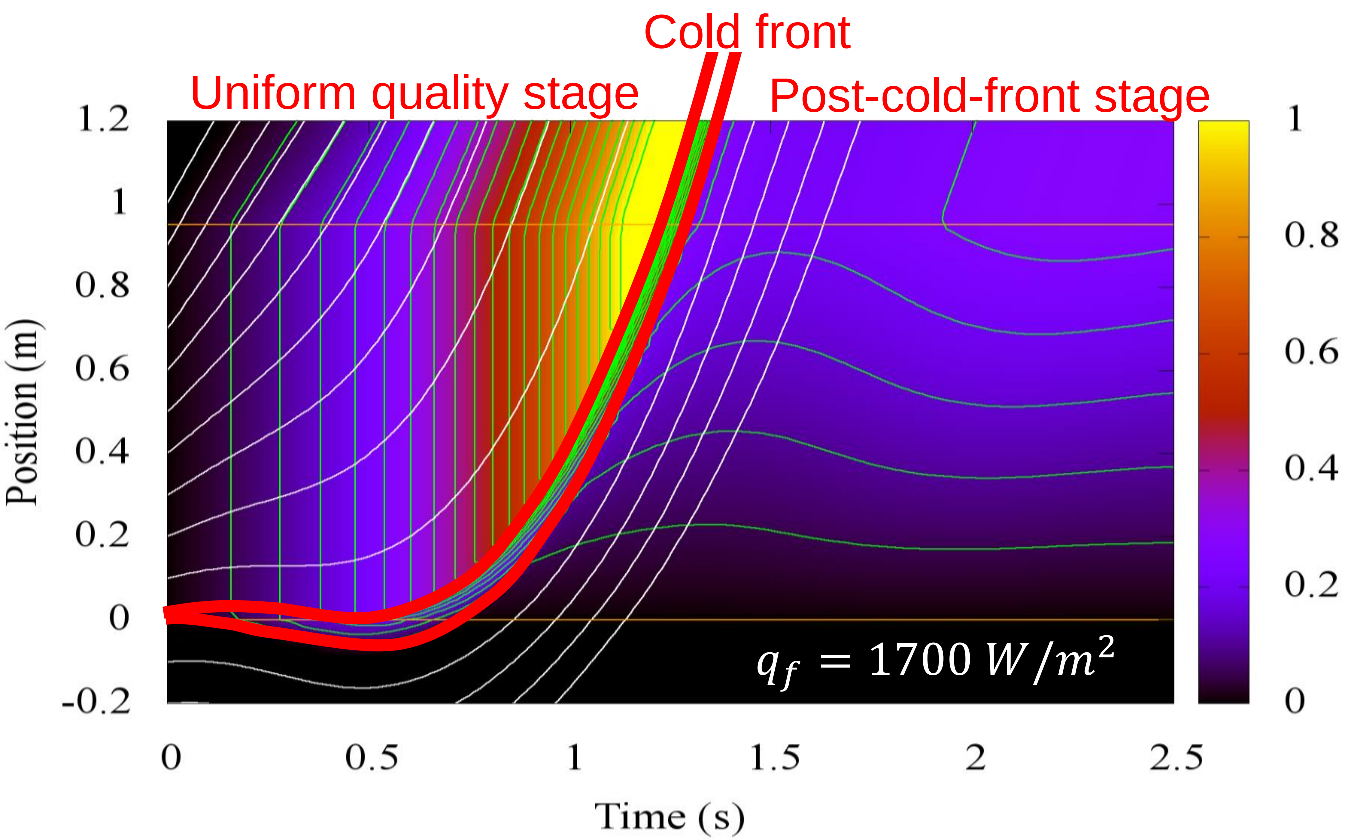
THE THERMOHYDRAULIC STAGES

We simulated the position and quality evolution of the particles from the measure of inlet velocity (Lagrangian approach)

$$\frac{dz}{dt} = u(z,t) = u_0(t) + \frac{4q\, v_{lg}}{D\, h_{lg}}\, z$$

$$\frac{dx}{dt} = \frac{4q}{D\, \rho\, h_{lg}} = \frac{4q}{D\, h_{lg}}\left(v_l + v_{lg}\, x\right)$$

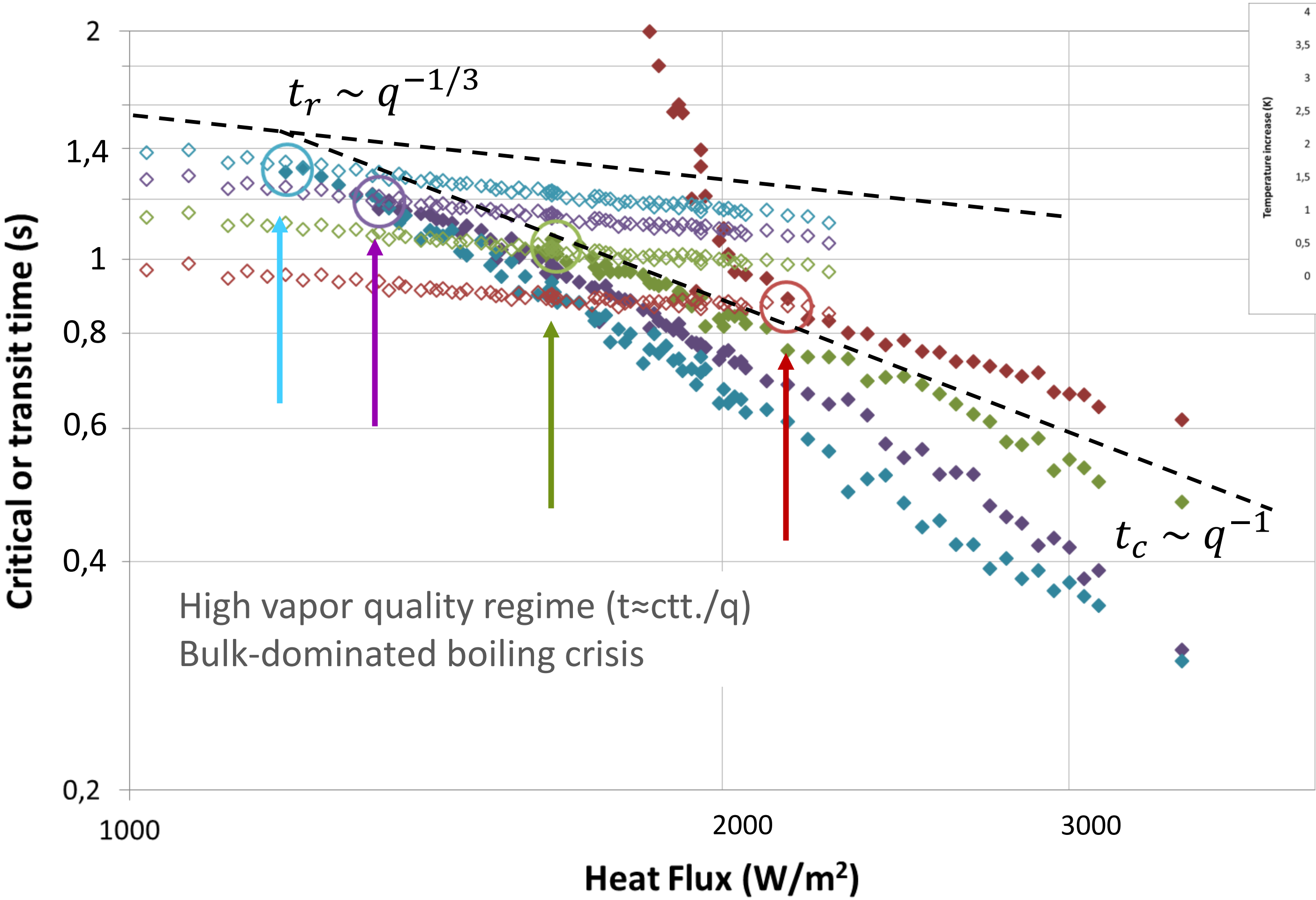


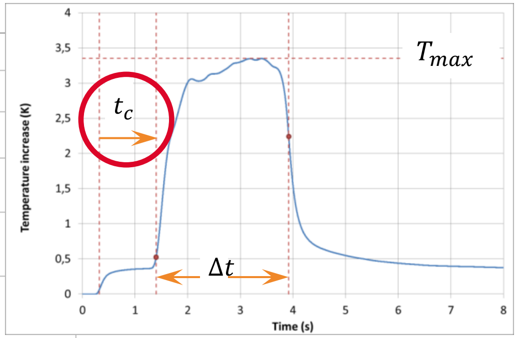


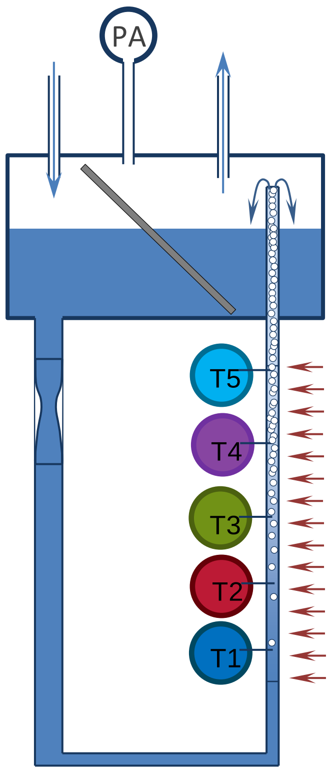
The end of the uniform quality stage is dictated by the inlet velocity evolution, which is generally not known *a priori*.

Hence the need of simulating fast power injection transient dynamics.

BOILING CRISIS INCIPIENCE HEAT FLUX







Boiling crisis incipience is the result of a competition between Critical time, t_c and the cold front transit time, t_r

Thus, **circulation plays a crucial role in boiling crisis**

MODELING OF TRANSIENTS IN NATURAL CIRCULATION LOOPS

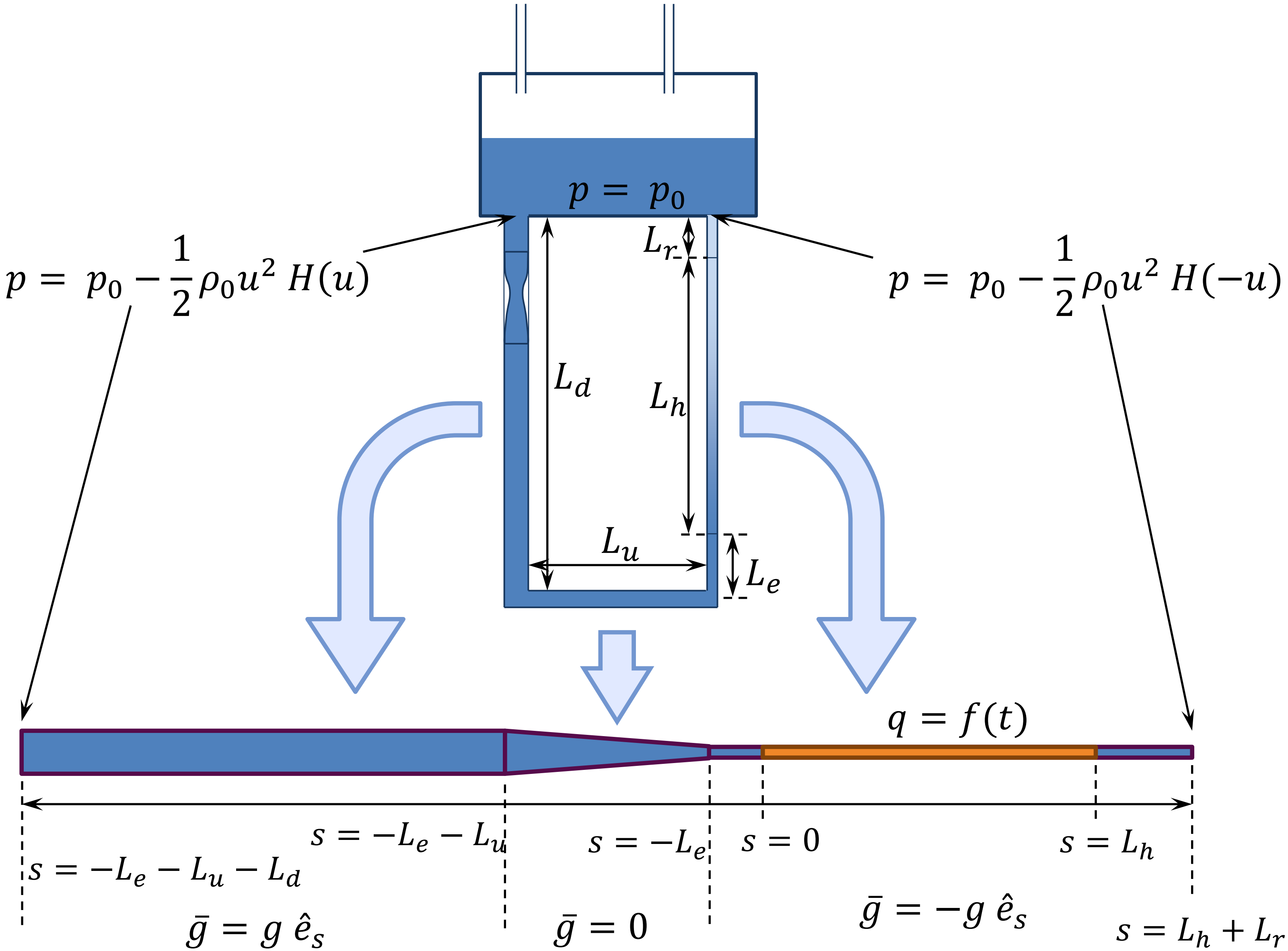
General procedure

- Definition of the assumptions of the model
- Development of the equations
- Implementation of the equations in a solver
- Simulation of experimental cases
- Validation of the method

Approach followed

- Departure point: time dependent homogeneous equilibrium flow model
- First approach: simplificiation of the equations by neglecting pressure effects on properties an in the energy equation
- Implementation in a comercial solver
- The validation arose questions on the validity of the pressure assumption
- Second approach: numerical coding of the full version of the HEM

1D FLOW REPRESENTATION OF THE LOOP



SIMPLIFYING THE HEM

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial\left(\rho u A\right)}{\partial s} = 0$$

$$\frac{\partial\left(\rho u\right)}{\partial t} + \frac{1}{A}\frac{\partial\left(\rho u^2 A\right)}{\partial s} = -\frac{\partial p}{\partial s} - \frac{\partial p_{fr}}{\partial s}\left(u,\rho\right) + \rho \mathbf{g}\cdot\mathbf{e}_s$$

$$\frac{\partial\left[\rho\left(e+\frac{u^2}{2}\right)\right]}{\partial t} + \frac{1}{A}\frac{\partial\left[\rho u A\left(h+\frac{u^2}{2}\right)\right]}{\partial s} = q + \rho \mathbf{g}\cdot\mathbf{u}$$

$$\rho = f_\rho^{h,p}\left(h,p\right) = \begin{cases} \rho_l \\ \left(\frac{h-h_l}{h_{lg}\rho_g} + \frac{h_g-h}{h_{lg}\rho_l}\right)^{-1} \end{cases}$$

$$h = e + \frac{p}{\rho}$$

- The fluid is at the saturation point everywhere
- No subcooling is considered
- Pressure time and space derivatives neglected in the energy balance (high heating rates)
- Kinetic energy is neglected in the energy balance
- Cross section area is uniform in each tube, it only changes abruptly at points

FROM RESEARCH TO INDUSTRY

cea

SIMPLIFYING THE HEM

The **energy conservation** gives: $\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial s}=\frac{q}{\rho}+u\mathbf{g}\cdot\mathbf{e}_s$

The neglecting gravity work and using the **mass conservation** law it results that velocity has space derivative only at heated points

$$\frac{\partial u}{\partial s}=\frac{v_{lg}}{h_{lg}}q=\Omega \longrightarrow u\left(s,t\right)=\begin{cases}\frac{A_h}{A(s)}u_0\left(t\right) & \text{if } s<0\\ u_0\left(t\right)+\Omega\left(t\right)s & \text{if } 0<s<L_h\\ \frac{A_h}{A(s)}\left[u_0\left(t\right)+\Omega\left(t\right)L_h\right] & \text{if } s>L_h\end{cases}$$

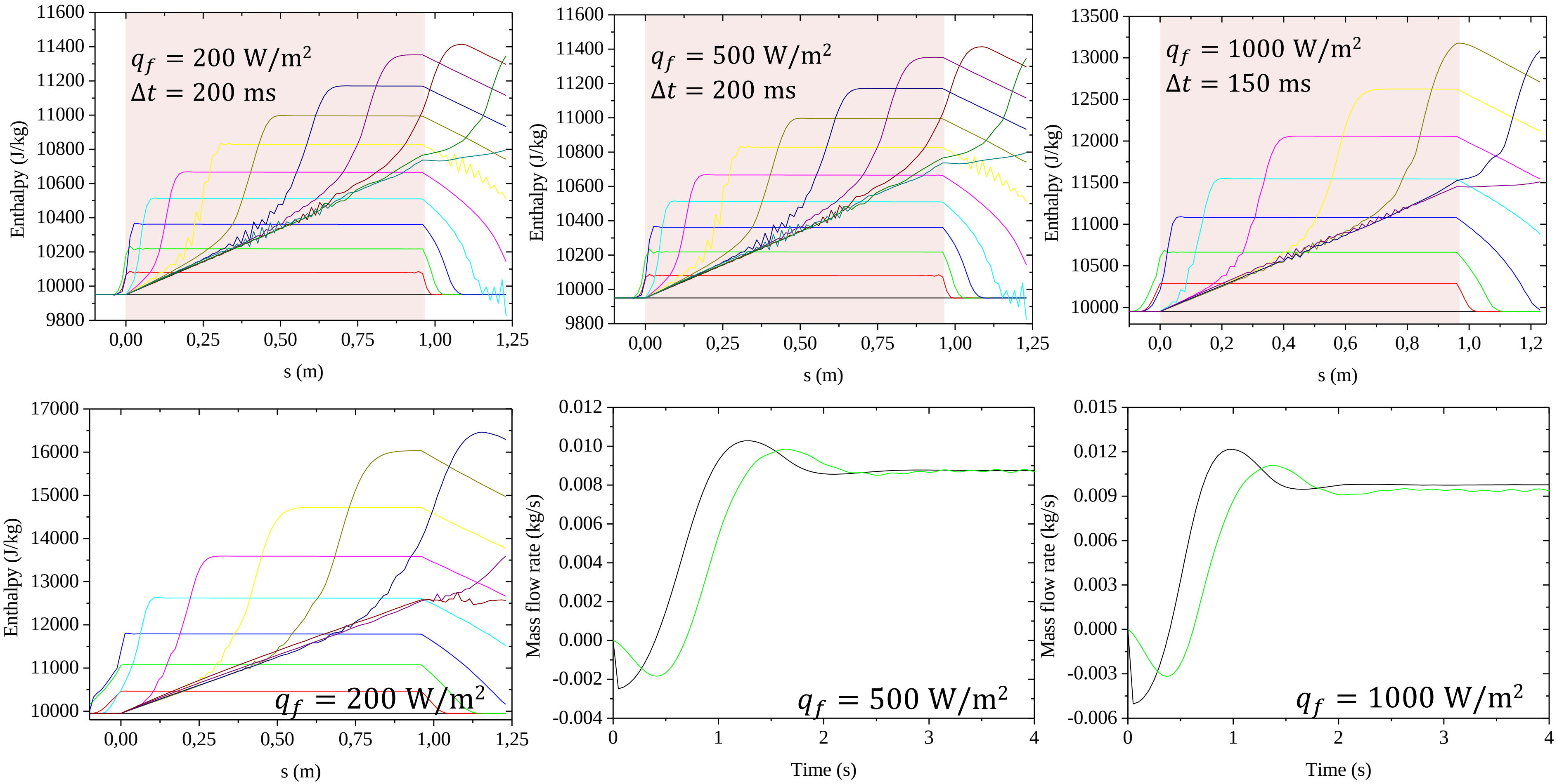
Defining $G=\int_{loop}\rho u\,\mathrm{d}s$, we can integrate the **momentum equation** to obtain

$$\frac{\mathrm{d}G}{\mathrm{d}t}=-\left(\rho u^2\right)_{out}+\left(\rho u^2\right)_{in}+p_{in}-p_{out}-\Delta p_{fr}-\Delta p_{sing.}+\int\rho\mathbf{g}\cdot\mathbf{e}_s\mathrm{d}s+\sum_i\Delta_i\left(\frac{\rho u^2}{2}\right)$$

From the def. of $G(t)$ there exists a **link between $\boldsymbol{G(t)}$ and $\boldsymbol{u_0(t)}$** and integrals of ρ:

$$u_0\left(t\right)=\frac{G\left(t\right)-\Omega\left(I_h+L_h\sum_k\frac{A_h}{A_k}M_k\right)}{\sum_i\frac{A_h}{A_i}M_i}$$

SIMULATED TIME EVOLUTION



The simulator is successful in representing transport, the uniform quality stage and the cold front. However it predicts an inlet velocity that evolves faster than measured.

Is this because of neglecting significant pressure effects at the beginning of the transient?

SOLUTION OF THE NON-SIMPLIFIED HEM

Numerical code in C for the solution of:

Treated as in steady state (Blasius)

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = \frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial s} = -\frac{\rho}{A}\frac{\partial (uA)}{\partial s}$$

$$\frac{\mathrm{D}u}{\mathrm{D}t} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s} = -\frac{1}{\rho}\frac{\partial p}{\partial s} - \frac{1}{\rho}\frac{\partial p_{fr}}{\partial s}(u,\rho) + \mathbf{g}\cdot\mathbf{e}_s \qquad \tilde{e} = e + \frac{u^2}{2}$$

$$\frac{\mathrm{D}\tilde{e}}{\mathrm{D}t} = \frac{\partial \tilde{e}}{\partial t} + u\frac{\partial \tilde{e}}{\partial s} = \frac{q}{\rho} + \mathbf{g}\cdot\mathbf{u} - \frac{1}{\rho A}\frac{\partial (puA)}{\partial s} \qquad p = f_p^{\rho,e}\left(\rho\,,\tilde{e} - \frac{u^2}{2}\right)$$

Up-wind explicit

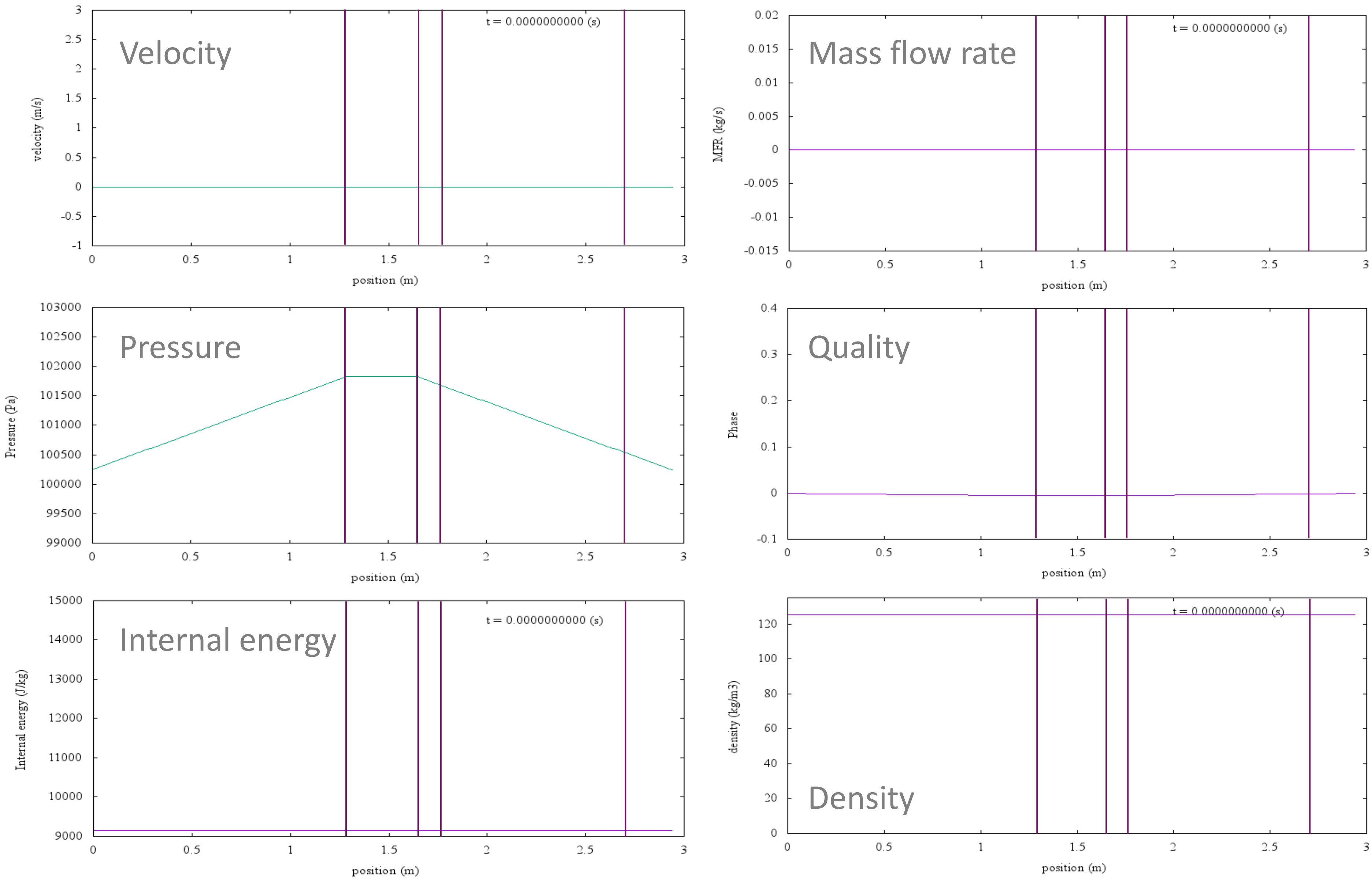
Space-centered semi-implicit

Hepak data was used
Subcooled liquid and two-phase

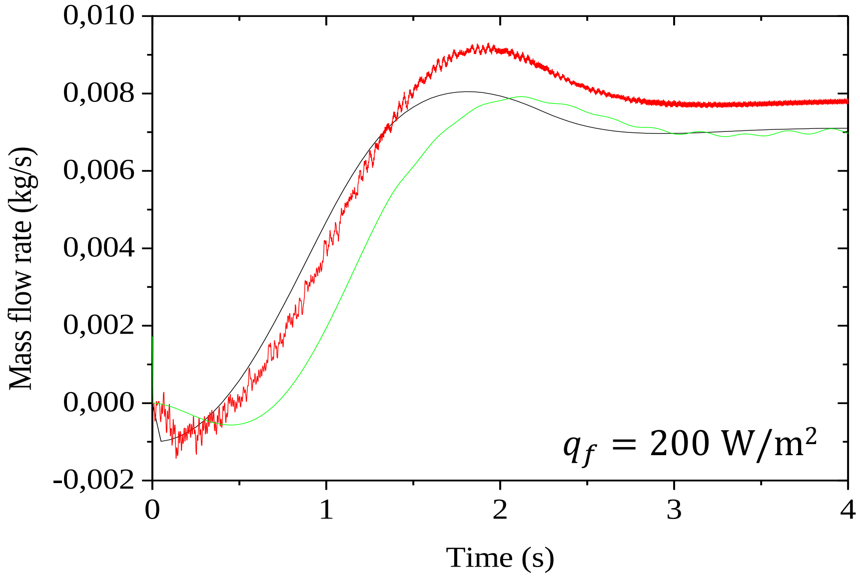
Non-linearities → iterative method

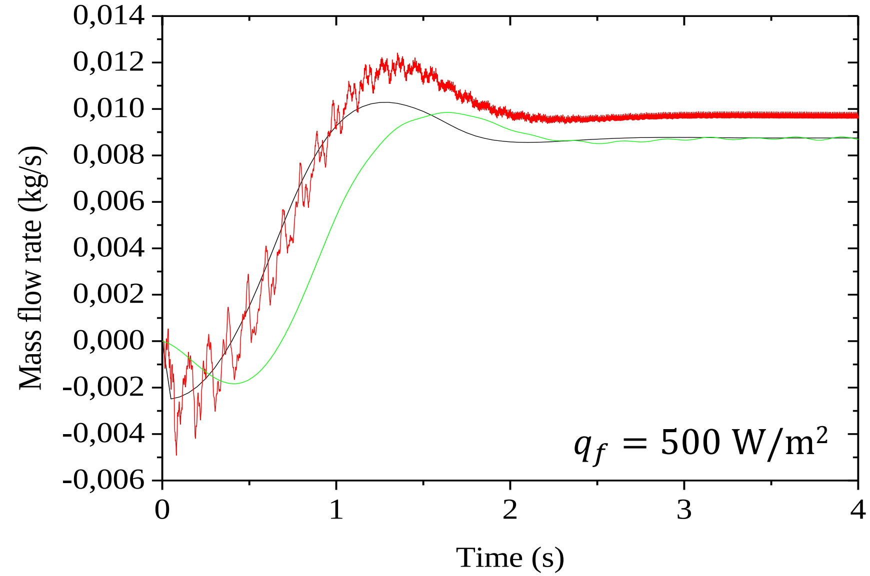
Outgoing flow		Incoming flow	
$\frac{\partial \rho}{\partial t} = -u\frac{\partial \rho}{\partial s}$	$p = p_{out}$	$\rho = \rho_{out}$	$p = p_{out} - \frac{u^2}{2}$
$\frac{\partial u}{\partial s} = 0$	$\frac{\partial \tilde{e}}{\partial s} = 0$	$\frac{\partial u}{\partial s} = 0$	$\tilde{e} = e_{out} + \frac{u^2}{2}$

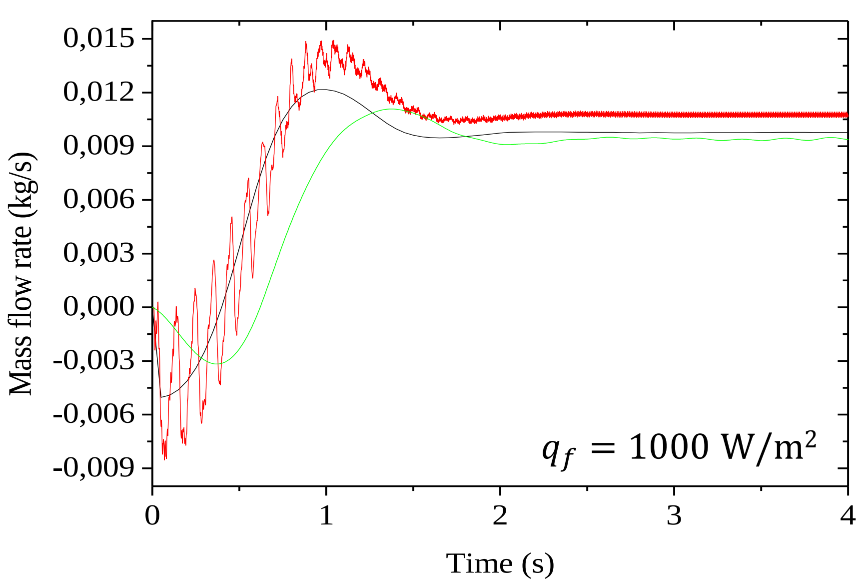
SIMULATED EVOLUTION



COMPARISON OF INLET MASS FLOW RATE PREDICITONS







- The inclusion of pressure effects adds « elastic » oscilations (probably due to non-considered transient friction effects)
- Considering the « exact » version of the HEM does not eliminate the phase shift with respect to experiments.
- Overestimation of void fraction and the buoyant forces (low velocity, intermediate void fraction)

CONCLUSION

Transient boiling crisis

- Transient BC can take place at lower heat flux than steady state BC.
- The stepwise-power-induced transients have to main stages:
  - Uniform evolution stage
  - Cold front stage
- Transient BC takes place because of a bulk-dominated mechanism during uniform stage.
- Competition between the two of them rules boiling crisis incipience

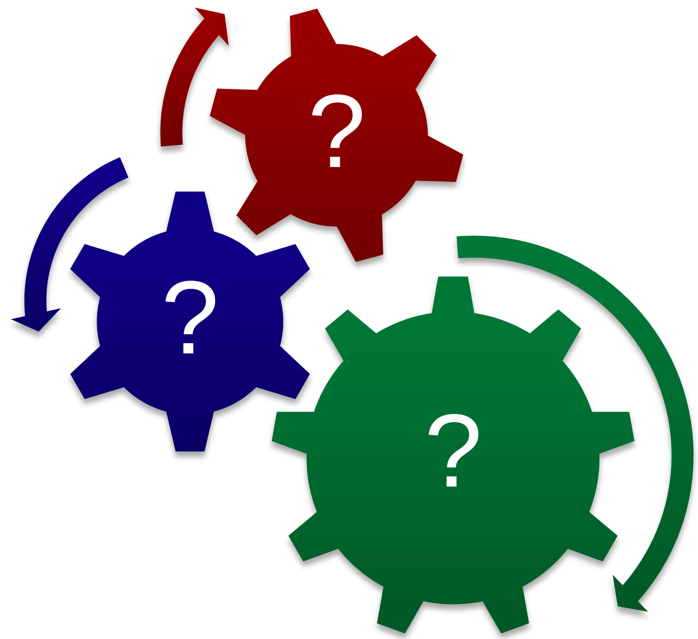
Thermohydraulic transient simulation

- Necessary for the estimation of transit time of the cold front
- Departure point: the HEM
- Two models: simplified (no pressure) and non-simplified
- The results of the two code are equivalent with respect to cold front transit times
- The HEM predicts too small transit times, overestimating the transient boiling crisis limits
- The HEM overestimates void fraction at low average velocity and intermediate quality.
- Better models are necessary.

FROM RESEARCH TO INDUSTRY

www.cea.fr

Thank you for your attention!



COMMISSARIAT À L'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES
DSM/IRFU/SACM
CENTRE DE SACLAY | 91191 GIF-SUR-YVETTE CEDEX
Etablissement public à caractère industriel et commercial | RCS paris B 775 685 019