MYRRHA Primary Heat Exchanger stability analysis

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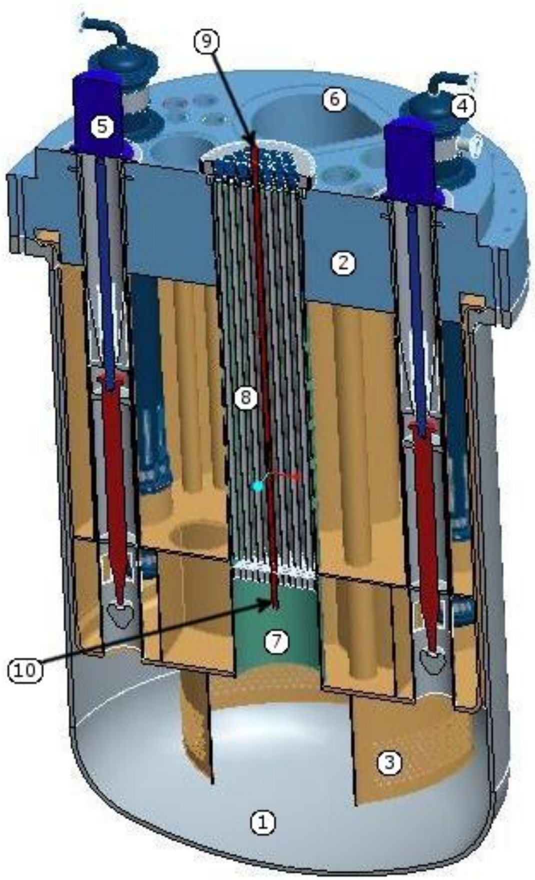
Contents

MYRRHA plant: purposes and general design

- MYRRHA: Multi-purpose hYbrid Research Reactor for High-tech Applications
- Pool-type Accelerator Driven System (ADS) with ability to operate also as critical reactor
- Liquid Lead-Bismuth Eutectic (LBE) as primary coolant
- Main purposes:
  - Flexible irradiation facility
  - Minor Actinides (MAs) transmutation demonstration in support of R&D on a "closed fuel cycle" (Generation IV requirement)
  - ADS demonstrator
  - Lead Fast Reactor demonstrator
  - (Pre-) Gen IV plant
- MYRRHA project recognized as high priority infrastructure for nuclear research in Europe

MYRRHA plant: purposes and general design

- MYRRHA primary system design current status (design revision 1.6):



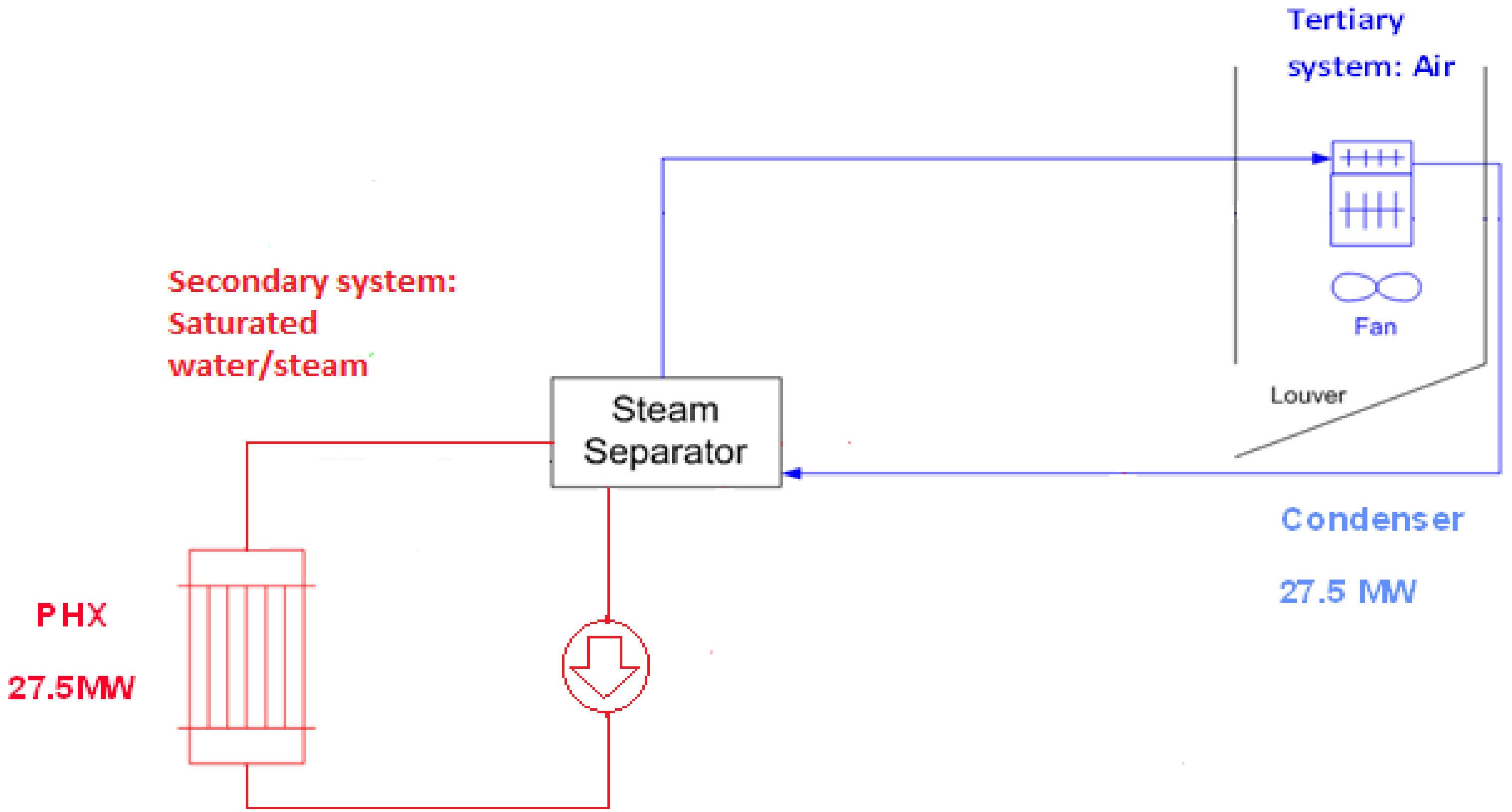
1. Reactor vessel
2. Reactor cover
3. Diaphragm
4. Primary heat exchanger
5. Pump
6. In-Vessel Fuel Handling Machine
7. Core barrel
8. Above Core Structure
9. Core plug
10. Spallation window

MYRRHA plant: purposes and general design

- Primary system:
  - Completely enclosed in primary vessel (pool-type)
  - Primary LBE flow path:
    - Lower plenum (270 °C)
    - Core (100 MW)
    - Upper plenum (~325 °C)
    - 4 Primary Heat eXchanger (PHX) units
    - 2 Primary Pumps (PPs)
    - Lower plenum
  - Cold plenum separated from hot plenum by Diaphragm supporting core barrel and components' penetrations
  - Above LBE free surface: Nitrogen layer

MYRRHA plant: purposes and general design

- MYRRHA secondary system (one loop out of four) design state of the art (developed in FP7 Central Design Team project):



MYRRHA plant: purposes and general design

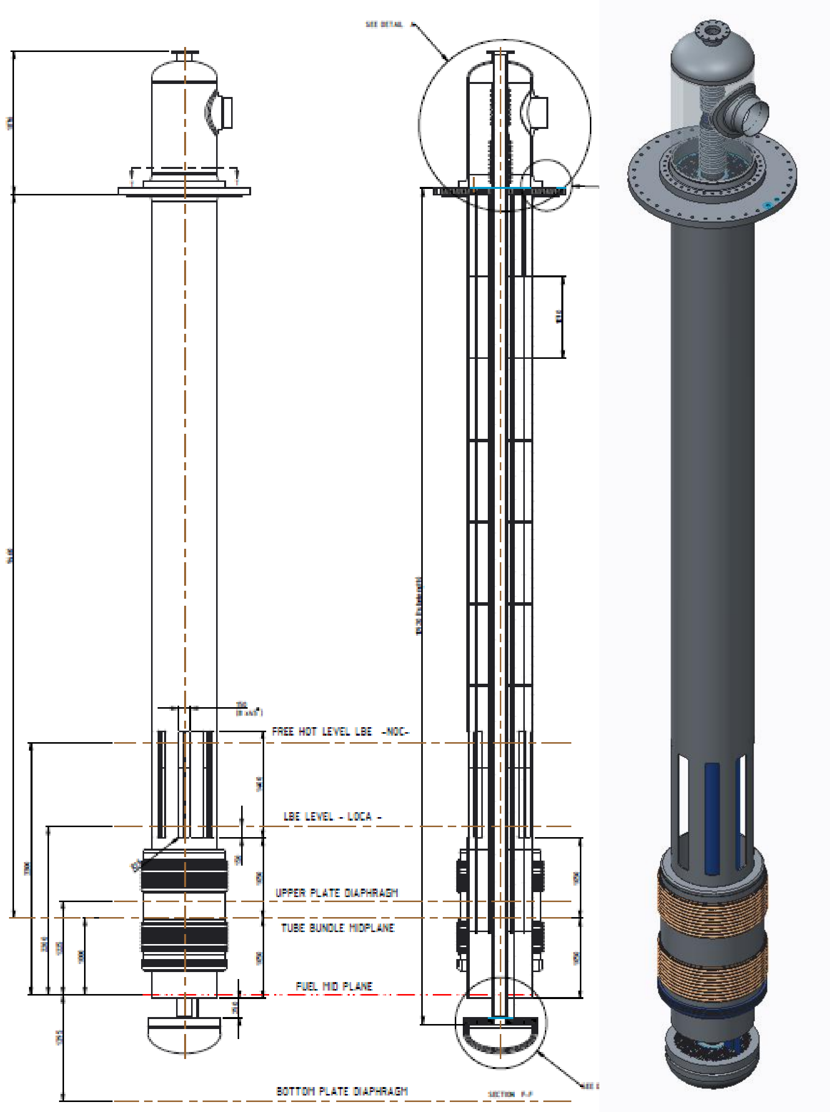
- Secondary system:
  - Four independent secondary loops (linked through PHXs)
  - Operated with forced flow two-phase water mixture (16 bar, 200 °C)
  - Secondary water flow path:
    - PHX inlet (~saturated conditions)
    - PHX outlet ($x \sim 0.3$, $\alpha \sim 0.9$)
    - Moisture separated in steam drum
  - In normal operation, secondary water temperature kept constant by control system (primary LBE temperature changing as a function of core loading)
- Tertiary system: dissipating heat to external environment through air condensers (forced circulation air fans)
- Condensed steam recirculated into steam drum

MYRRHA plant: purposes and general design

- MYRRHA plant designed for 110 MW as nominal power:
  - 100 MW → core power
  - 10 MW → additional heat sources:
    - In Vessel Storage Tank (IVST)
    - Po decay heat
    - Pump power
    - γ heating
    - Spallation target power
- Normal operation → all three cooling systems designed to operate in forced circulation
- Accidental conditions → DHR in full natural circulation (three cooling loops operating in passive mode)
- Two systems to remove decay heat power:
  - DHR-1: secondary and tertiary systems operating in passive mode
  - DHR-2: Reactor Vessel Auxiliary Cooling System (RVACS)

MYRRHA PHX general description

- MYRRHA PHX: counter-current shell-and-tube concept:
  - 684 stainless steel (AISI 316L) tubes
  - Wall thickness = 1 mm
  - 2 tube plates (thickness = 80 mm)
  - Double-walled central feedwater pipe
  - Double-walled bottom head
  - Top head
  - External shroud



MYRRHA PHX general description

- MYRRHA PHX main geometrical and thermal-hydraulical parameters:

Parameter	Unit	Value
Power in one PHX	MW	27.5
Shroud external diameter	mm	850
Shroud internal diameter	mm	820
Feed water pipe external diameter	mm	200
Water tubes number	-	684
Water tubes pitch	mm	26
Water tubes external diameter	mm	16
Water tubes internal diameter	mm	14
Thickness of water tubes	mm	1
Total length of water tubes	mm	10920
Active length of water tubes	mm	2100

MYRRHA PHX main geometrical parameters

Parameter	Unit	Value
PHX LBE inlet temperature	°C	325
PHX LBE outlet temperature	°C	270
LBE safe shutdown temperature	°C	200
PHX LBE mass flow rate	kg/s	3450
PHX water inlet temperature	°C	200
PHX water outlet temperature	°C	201.4
PHX water mass flow rate	kg/s	47
PHX water pressure	bar	16
PHX water outlet quality	-	0.3
PHX water outlet void fraction	-	0.9
LBE velocity	m/s	0.93
Primary side LBE pressure drop	bar	0.04
Water outlet velocity	m/s	3.3
Steam outlet velocity	m/s	18.63
Secondary side water pressure drop	bar	0.95

MYRRHA PHX main thermal-hydraulical parameters

MYRRHA PHX general description

- MYRRHA PHX design presents the following characteristics:
  - Heat exchange mostly limited to the PHX "active length" (~2.1m) placed between inlet and outlet
  - Wall developed two-phase flow inside the PHX tubes from the inlet up to the top
  - High aspect ratio (L/D) providing a better counter-current flow development through the bundle
  - Only one tube plate located under LBE
  - Easier inspection and repair

MYRRHA PHX general description

- Potential disadvantages coming from such design approach:
  - High two-phase pressure drop in the tube bundle, with potential increase of dynamic instabilities
  - Notable tube length (~11m) possibly generating important mechanical stresses (weight and thermal induced) in the tube plates and vibrational stresses in the tube bundle
  - Tube bundle in contact with the free surface level leading to possible problems due to differential thermal expansion and level fluctuations → thermal fatigue

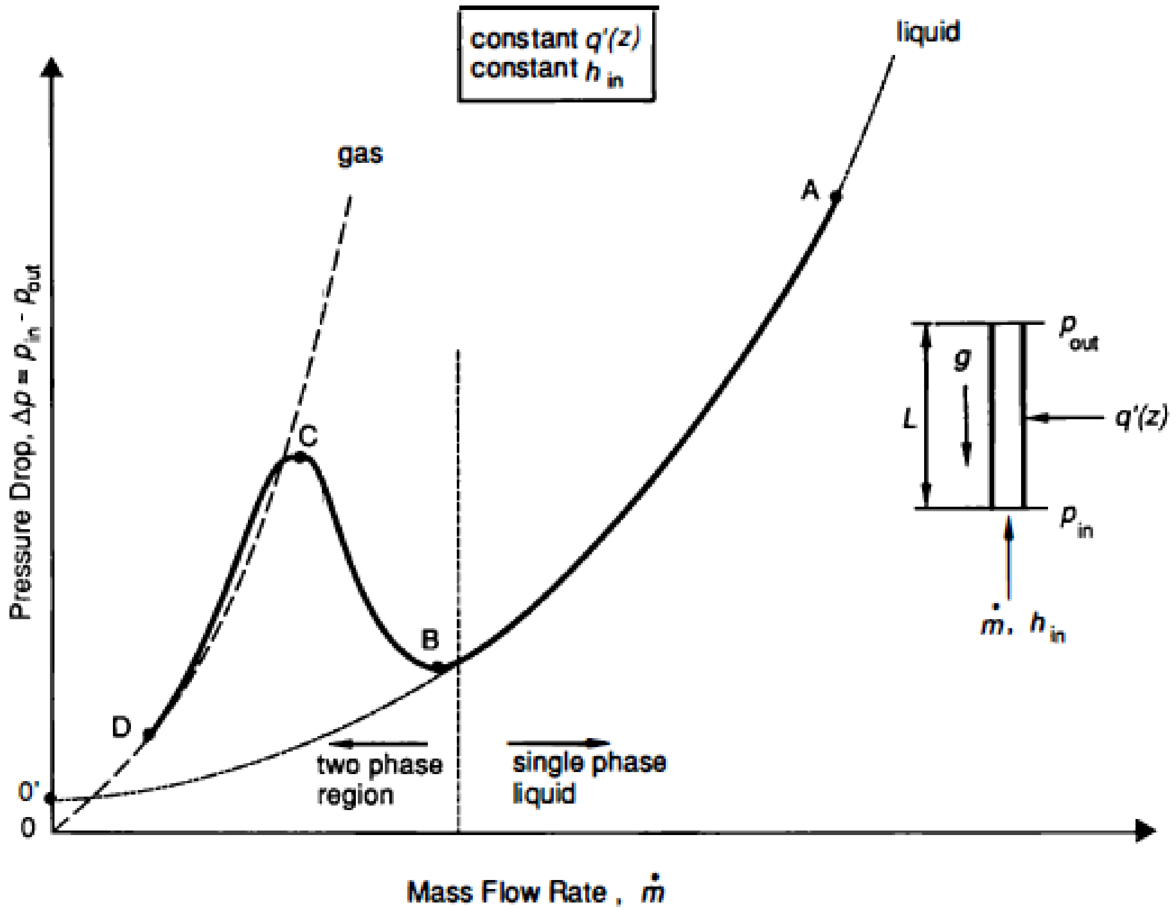
Main analysis findings and outcome

- MYRRHA PHX presents the following main features:
  - Ledinegg instability not a concern because of the low exit quality
  - DWO instability appearing in the system because of the limited water subcooling temperature and the extended two-phase region
  - Partial instability between certain Q/m intervals where slug flow regime prevails in the active tube section
- By placing an orifice with a diameter ~4.7 mm, it is possible to limit to some extent the unstable behavior of the system
- Induced instabilities do not respect the chosen stability criterion
  - A design modification (or a different stability criterion) should be considered

Two-phase flow instabilities

- Two kinds of instabilities can be found in a boiling (2ϕ) tube bundle of an HX:
  - Static instability
  - Dynamic instability
- Among these, three instability types identified for MYRRHA PHX:
  - Ledinegg instability: region of Δp-m characteristic curve allowing for more than a single solution, not always stable
  - Density wave instability: triggered by difference in density between the subcooled liquid entering the channel and the two-phase mixture exiting → transient inertia, lags and feedbacks between boiling channel parameters (mass flow rate, vapor generation rate, pressure drop)
  - Flow regime-induced instability: caused by extended operation in specific flow regimes

Ledinegg instability



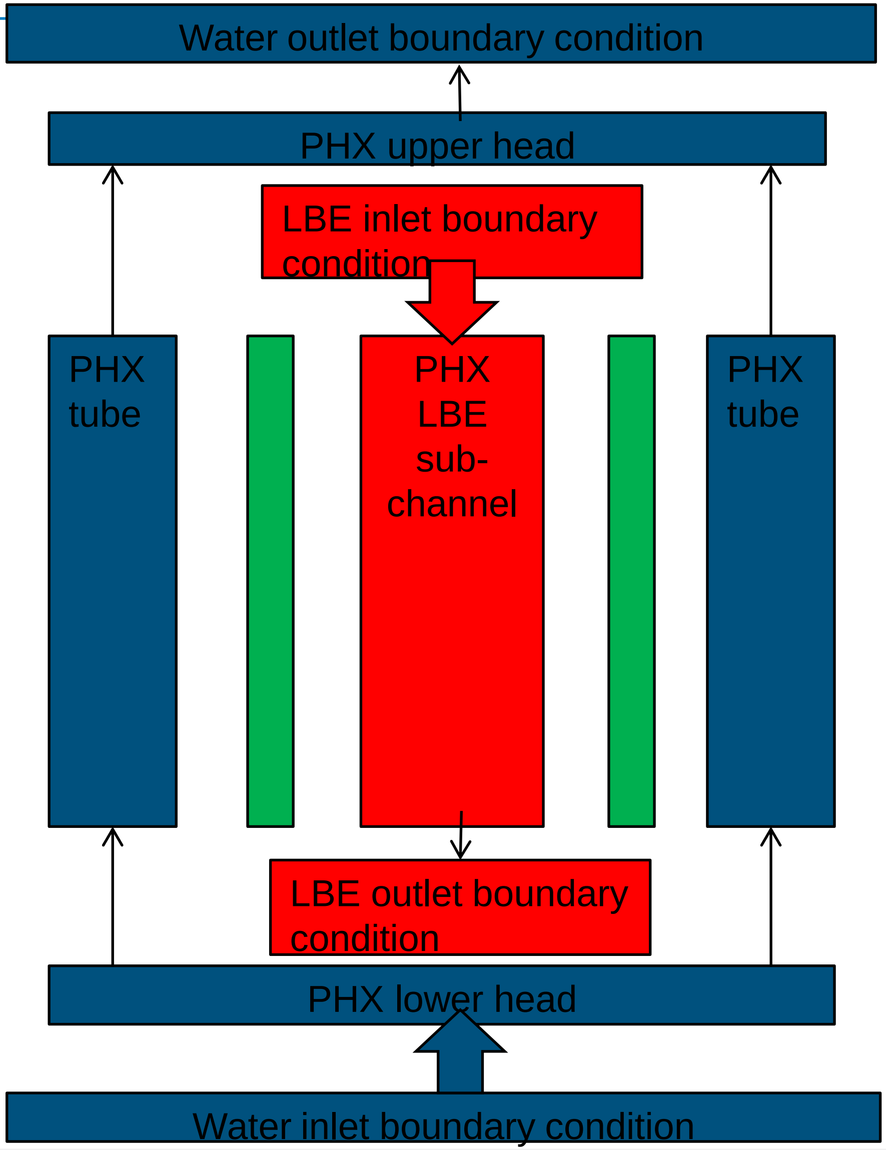
- Region A-B and region C-D: stable (~parabolic characteristic)
- Region B-C: unstable (operating point drifting toward B or C in case of perturbation

Ledinegg instability

- Ledinegg instability studied through analytical models
- System experiencing Ledinegg instabilities in conditions far from normal operation (< 25% mass flow rate)
- Stability assured by low exit quality (~0.3)
- In all the operating conditions, the working point of the system falls in a perfectly stable range:
  - Mass flow rate per tube: 0.07 kg/s
  - Tube pressure drop: 0.95 bar
- DHR conditions: PHX power input considerably lower than normal operation → Ledinegg instability not an issue

Density wave oscillation instability

- DWO instabilities studied through RELAP5-3D simplified model
  - Real geometry has been assumed for PHX tubes:
    - Correct dimensions
    - Correct local pressure drop factors (Idel'chik)
- Not good response from the DWO instability analysis
  - Nominal flow and subcooling conditions: ~ 60% maximum power
  - Increased subcooling: < 10% maximum power



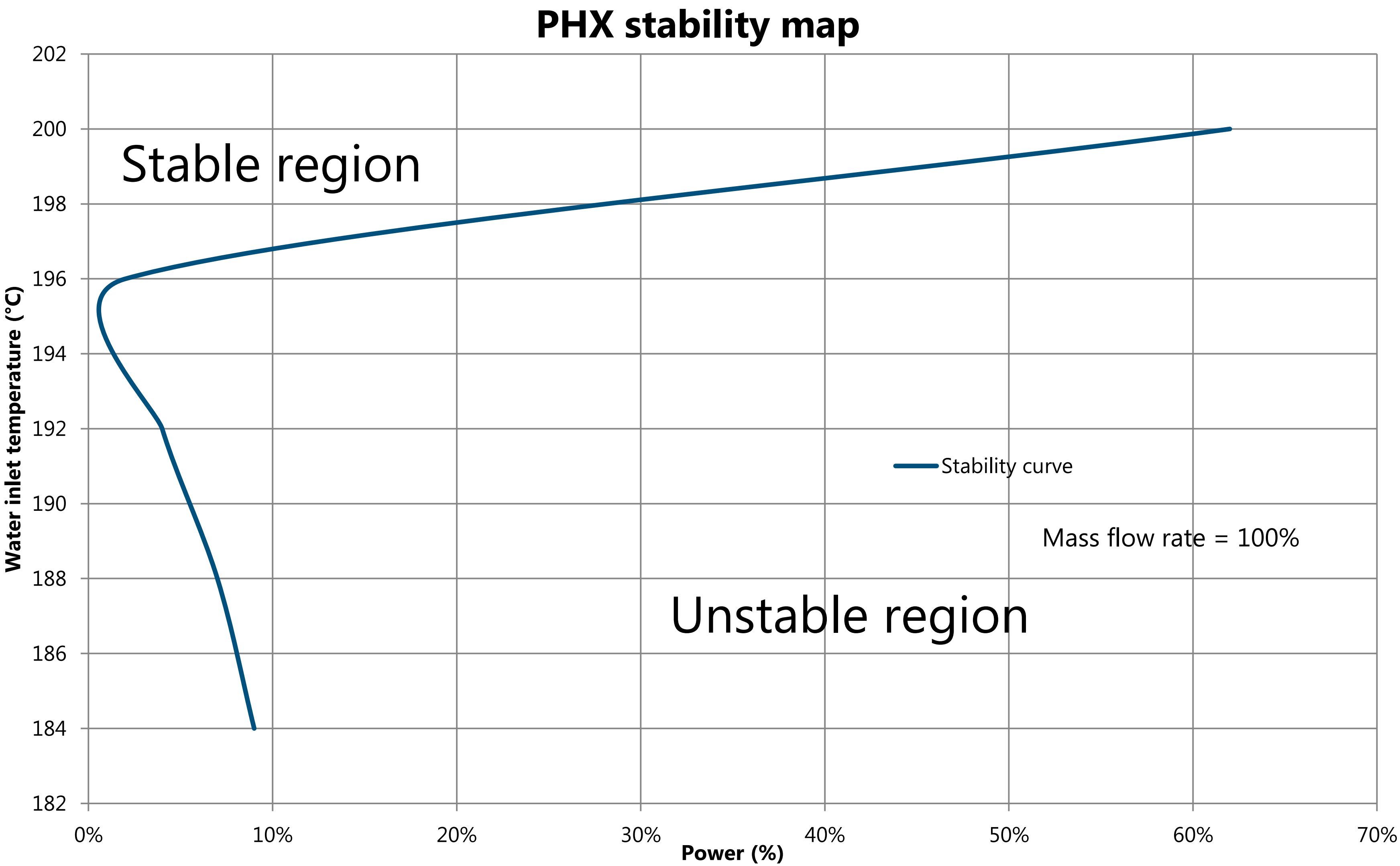
Density wave oscillation instability – Parameters effect

- General effects of different parameters on system stability against DWO instabilities:
  - Outlet quality increase has always a destabilizing effect → thermal power increase and/or mass flow rate decrease have a destabilizing effect
  - Inlet subcooling increase has a stabilizing effect at high subcoolings but a destabilizing effect at low subcoolings
  - System pressure increase has a slight stabilizing effect but, causing also other variations, the final outcome is not obvious
  - Inlet throttling (in monophase region) increases stability
  - Outlet throttling (in two-phase region) reduces stability

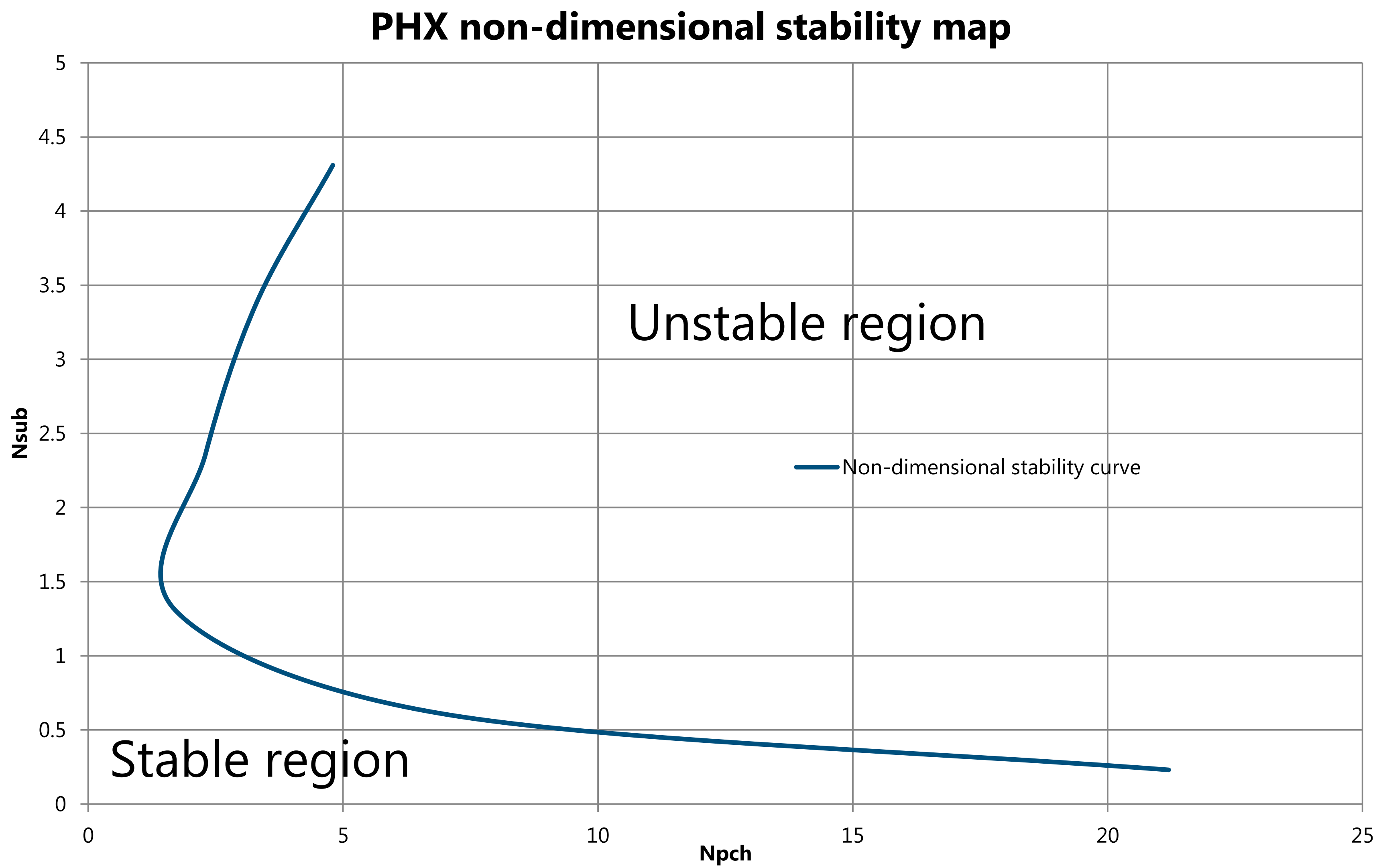
Density wave oscillation instability – Parameters effect

- Non-dimensional numbers introduced to account for all parameters' variations in a 2-D representation:
  - Phase change number (N_{pch}):
    - $N_{pch} = \frac{q}{m*h_{lv}} * \frac{v_{lv}}{v_l}$
  - Subcooling number (N_{sub}):
    - $N_{sub} = \frac{h-h_f}{h_{lv}} * \frac{v_{lv}}{v_l}$
- Advantages of the non-dimensional numbers use:
  - Possibility to include all the parameters' effects through ratios
  - Only two numbers required

Density wave oscillation instability

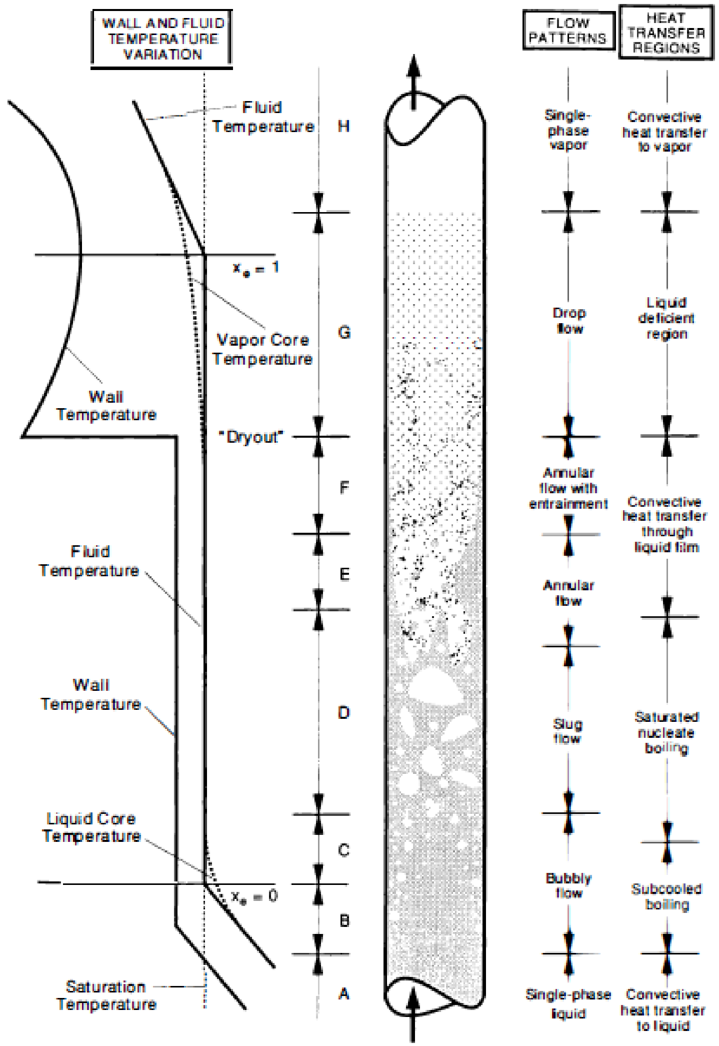


Density wave oscillation instability – Stability map

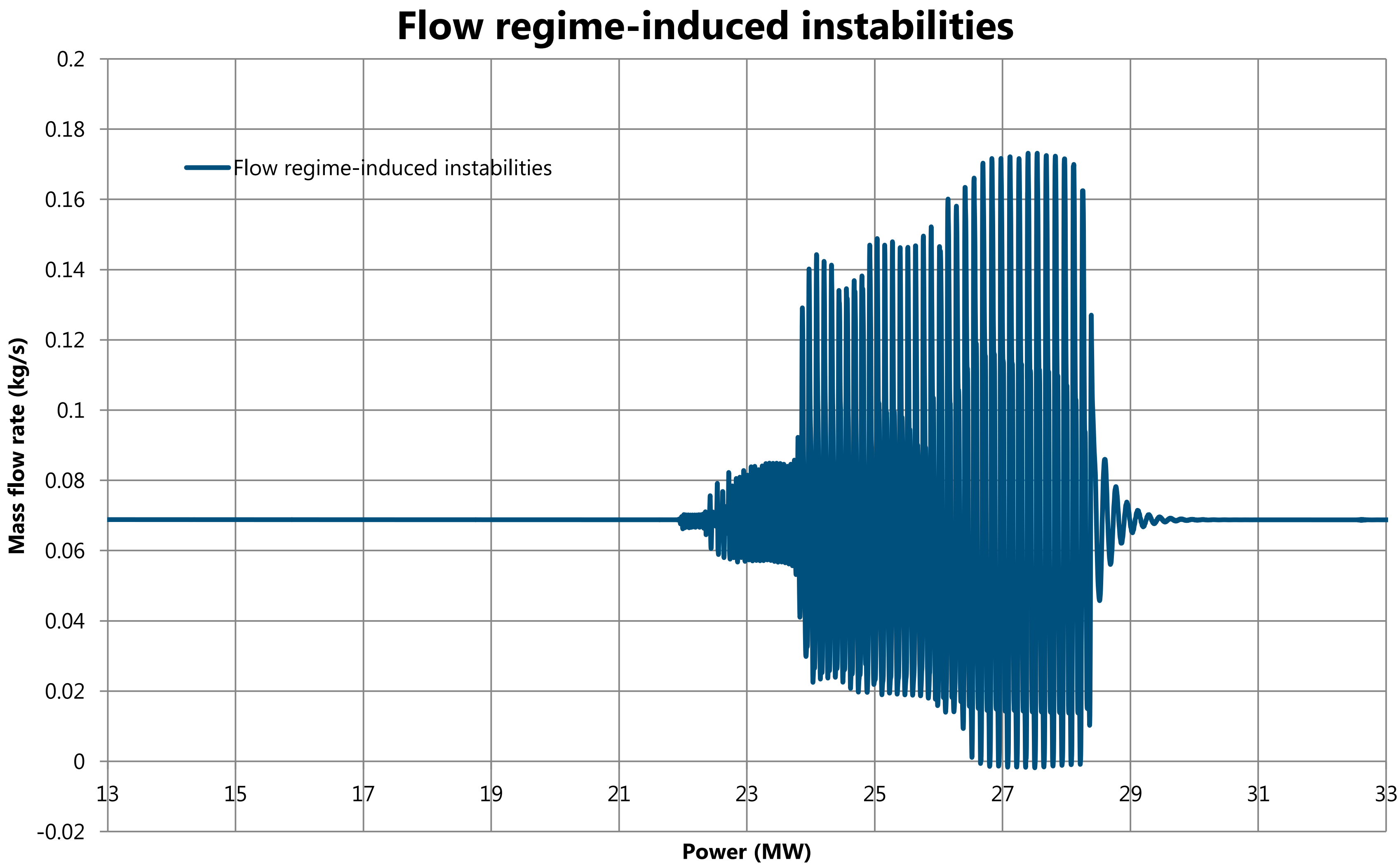


Flow regime-induced instabilities

- In case PHX active length majority is in two-phase slug flow regime (certain Q/m specific interval, function of subcooling) → channel flow becomes unstable
- Annular flow more stable → reducing flow (or increasing power) resolves flow-induced instability
- Important for low power operation or for start-up sequence



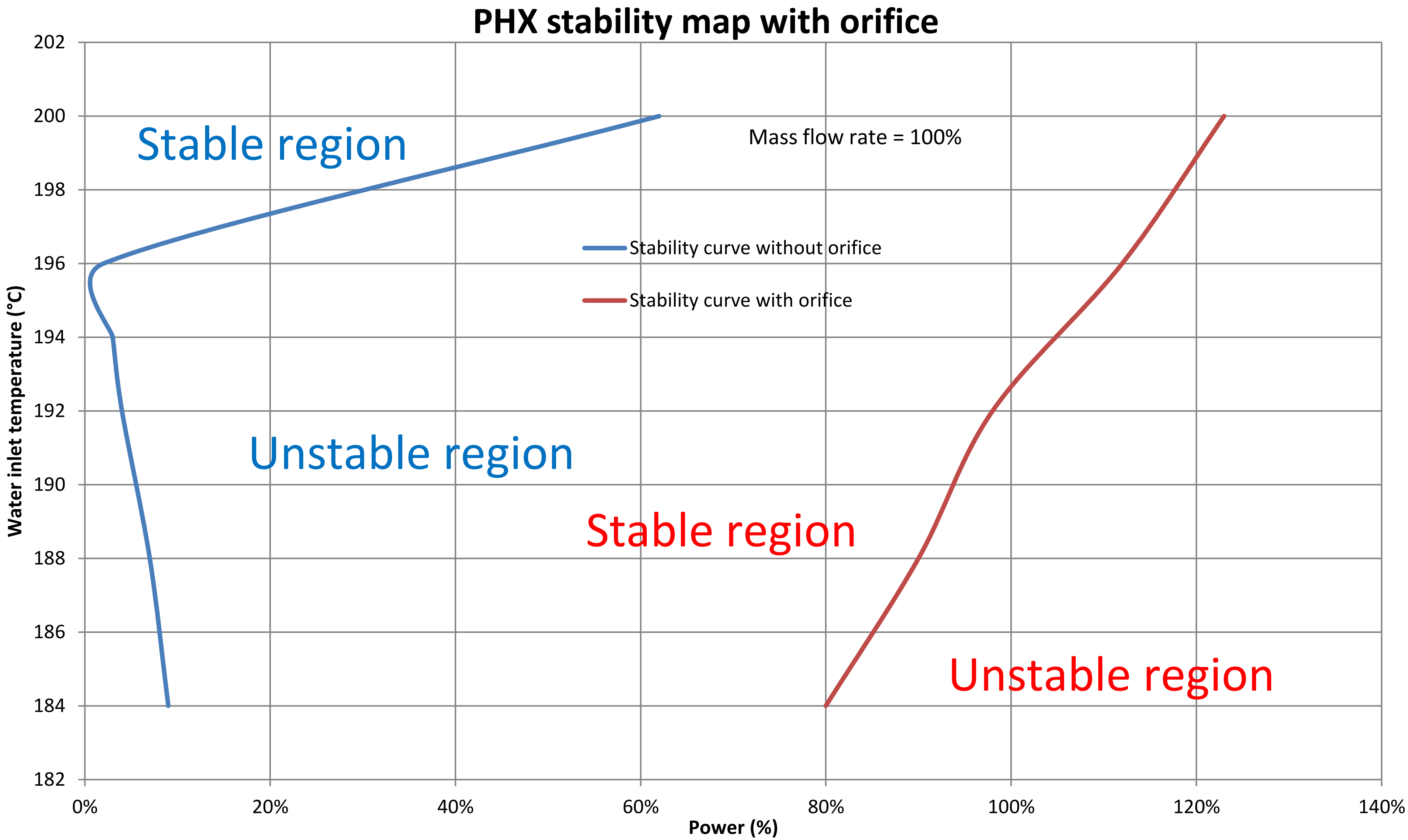
Flow regime-induced instabilities



Towards stability – Orifice dimensioning

- To avoid DWO instabilities, usual best practice solution is increasing the local pressure drop in the monophase region → placing an orifice at tube inlet
- By assuming a local pressure drop factor K = 120, an orifice with the following dimensions has been identified (Idel'chik):
  - Length = 80 mm (same as lower tube plate)
  - Diameter = ~ 4.7 mm (about 30% of tube diameter)
- Stability map is shifted towards right (increased stability range)
- Little influence found by further increase of orifice local K factor (→ reducing orifice diameter) beyond K = 120, but potential problems with local water velocity

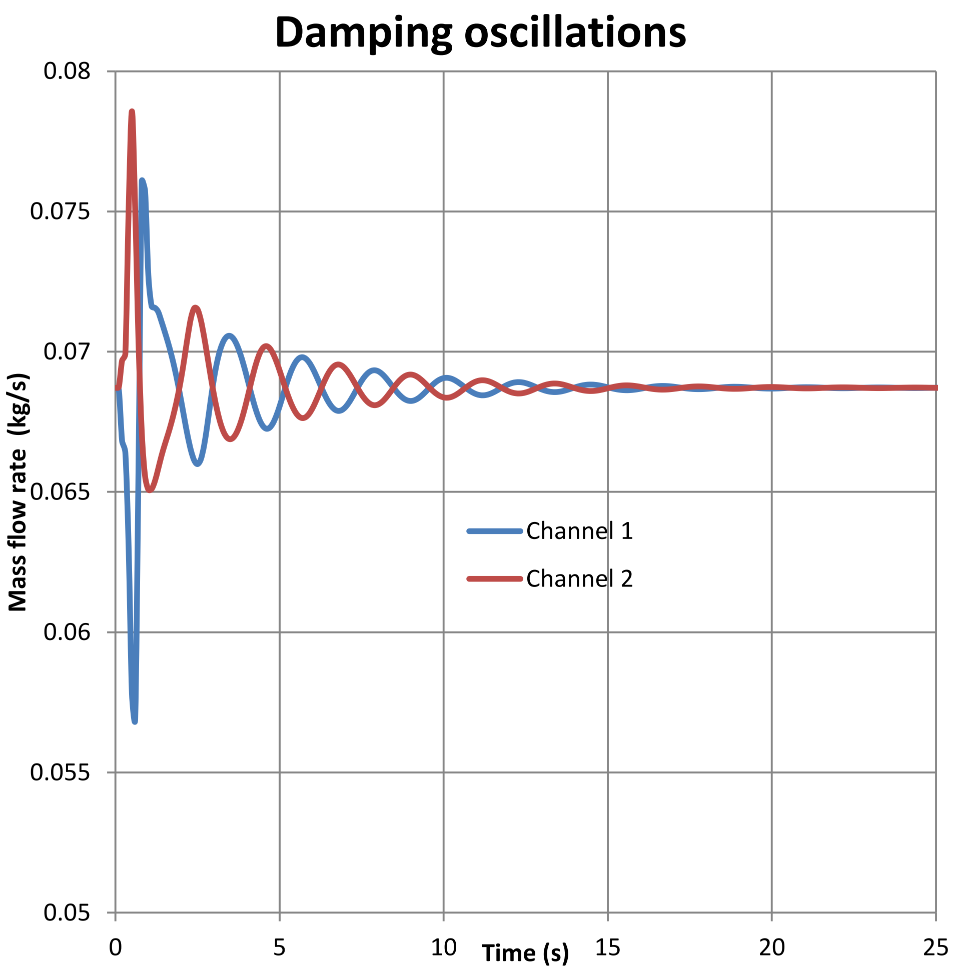
Towards stability – Stability map with orifice

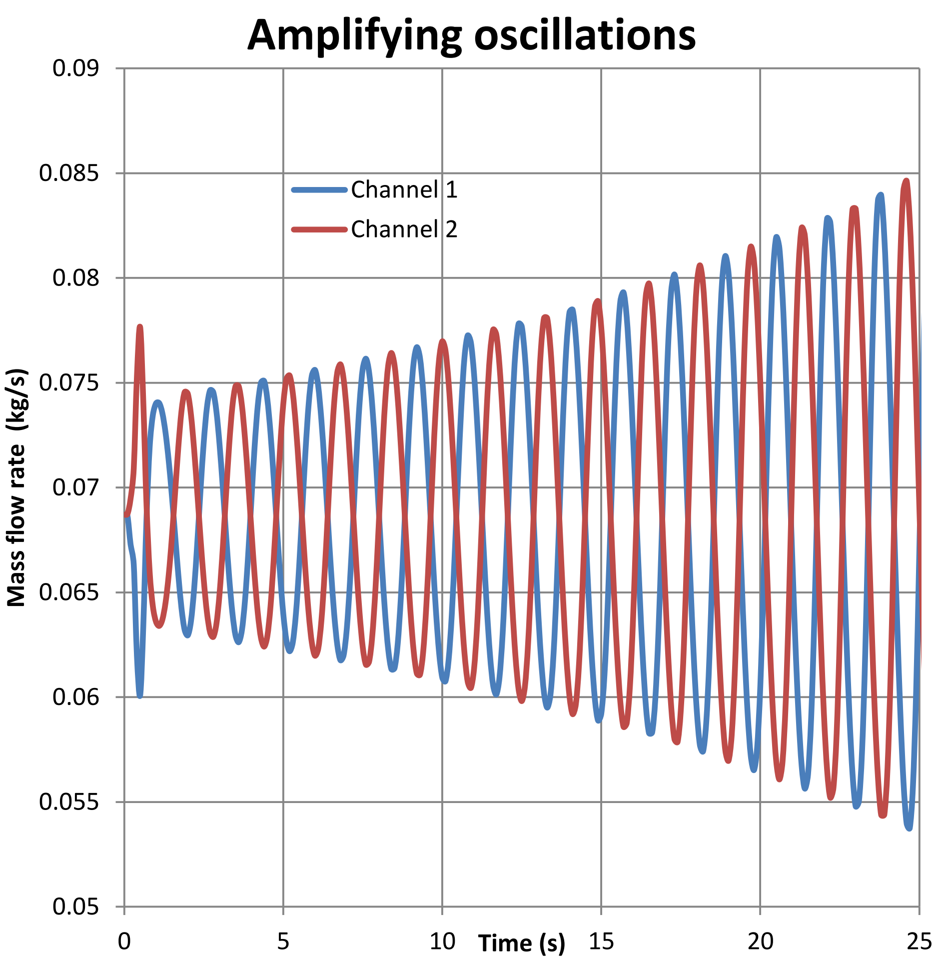


Induced instabilities – Stability criterion

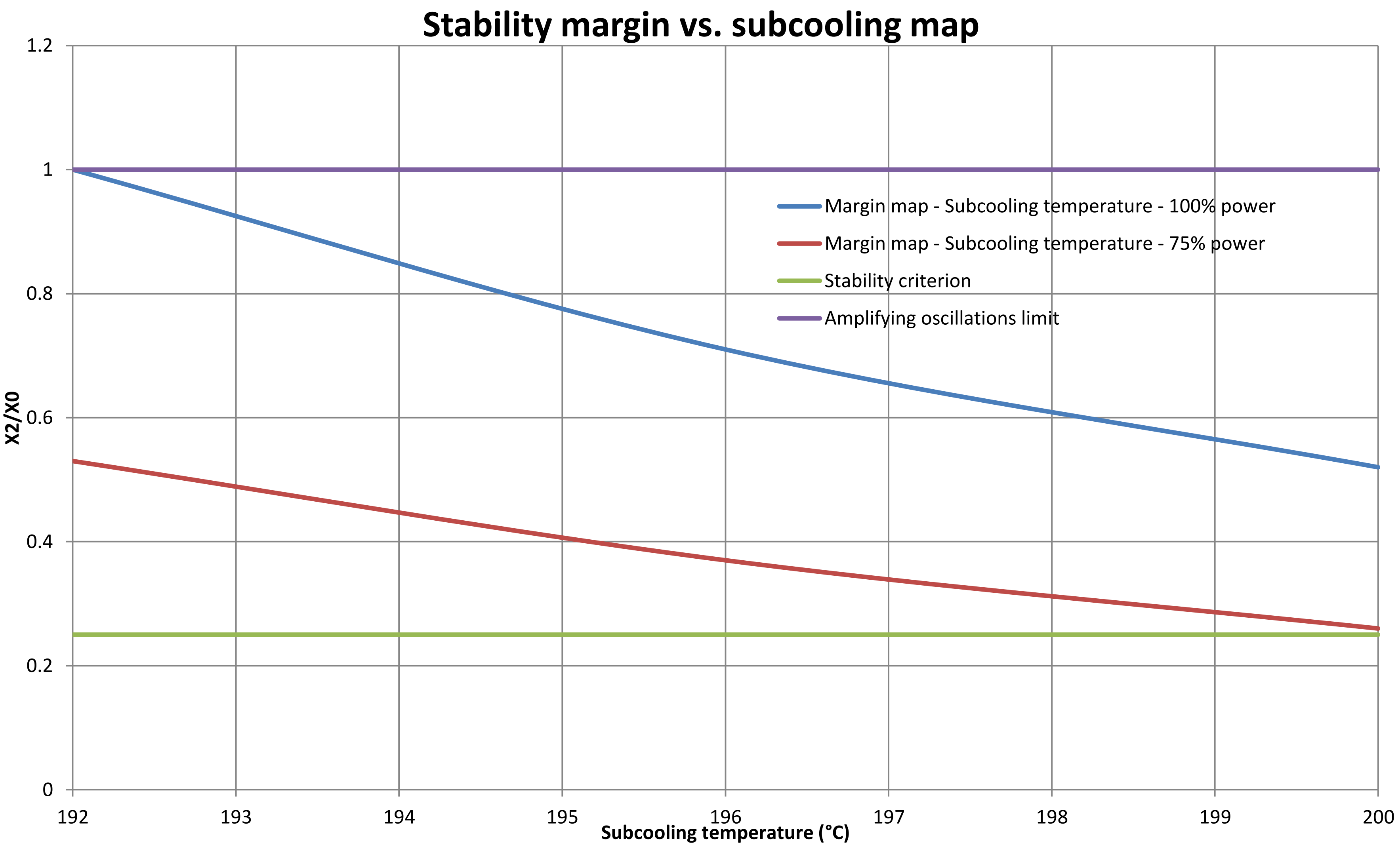
- Resolving (or mitigating) different instabilities is not enough
- Additional design requirement: stability to induced perturbation
  - Local mass flow rate disturbances
  - Local power spikes
- An induced instability usually appears at power levels found to be stable for DWO
- Possible consequences:
  - Amplifying oscillations
  - Damping oscillations
- Stability criterion proposal (from BWR technology):
  - $X_2/X_0 < 0.25$ (X_n = amplitude of oscillations)
- Mass flow rate perturbation simulated through a valve placed at inlet of one channel and experiencing a closing cycle shaped as half-cosine (0.4 s)

Induced instabilities – Typical profile

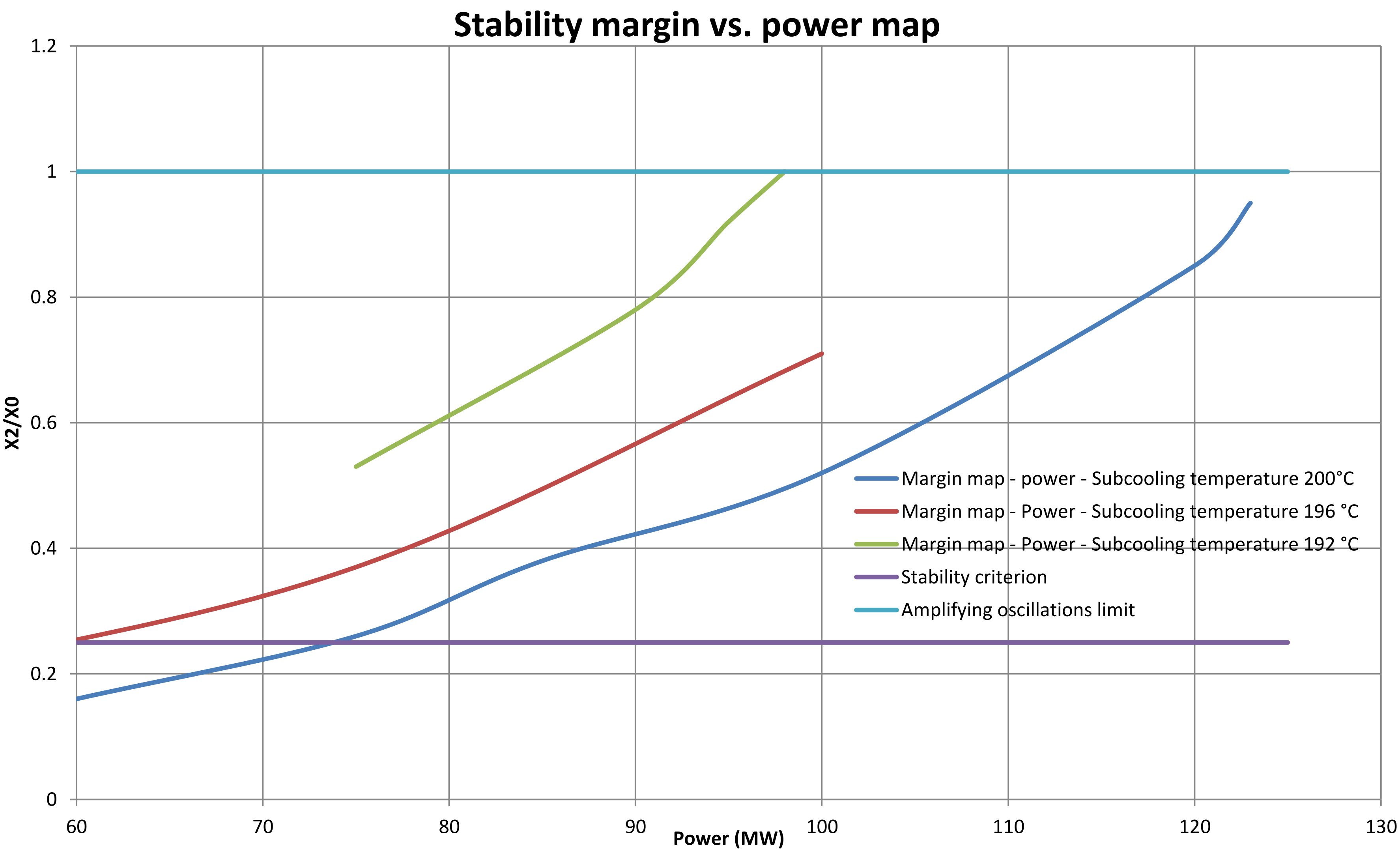




Induced instabilities – Margin map vs. subcooling



Induced instabilities – Margin map vs. power



Induced instabilities – Outcome

- Stability to induced perturbations is obtained in all normal operation conditions (with orifice K = 120)
- Respect of induced instability criterion (with orifice K = 120) is only possible in specific conditions
- Induced oscillations become amplified in case of:
  - Subcooling < 192 °C
  - Power > 123%
- Potential solutions:
  - Adoption of new (less stringent) criterion
  - Design modifications

Main analysis findings and outcome

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Conclusions and recommendation

- MYRRHA PHX behavior against instabilities is overall satisfactory
- Parameter values relatively far from the nominal conditions must be avoided
- Recommendation from stability analysis:
  - Avoid the slug flow regime during normal operation through adoption of suitable Q/m values at all times
  - Obtain a relatively low subcooling temperature at the PHX inlet through pressure losses and/or heat sources in the feedwater line

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