19th Topical Conference on Radio Frequency Power in Plasmas, Newport

Max-Planck-Institut für Plasmaphysik
EURATOM Assoziation

Development of arc detection for ITER

Rodolphe D’Inca

With contributions from:

R. Pinsker, I. Monakhov, P. Jacquet, S. Huygen, M. Vrancken, T. Mutoh, K. Saito, P. Dumortier, G. Berger-by, S. Wukitch, R. Wilson, F. Durodie, D. Rasmussen, J. Caughman, R. Goulding, H. Faugel, V. Bobkov, F. Braun, H. Fünfgelder, G. Siegl, B. Eckert.

Outline

Part 1 – Basics of arcing in ICRF systems

Arc evolution, interaction with RF components

Part 2 – The classical way of detecting arcs

The simplest method for detection and its limits

Part 3 – Advanced detectors

Family tree, Pros and Cons of each type

Part 4 – Engineering of the ITER Arc Detection System

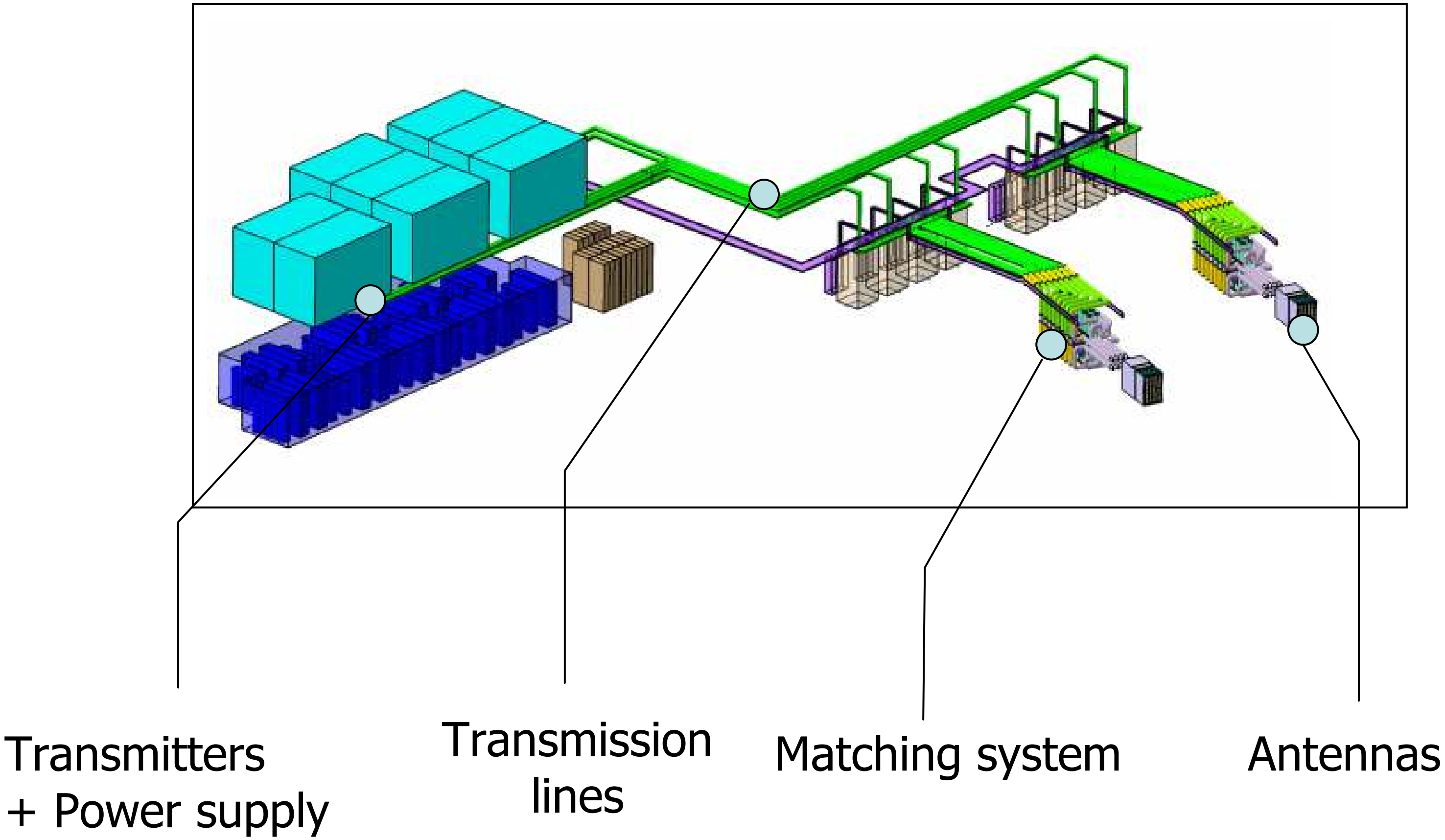
Requirements, Design and Justification

~ Prelude ~

A practical approach of arcs in ICRF systems

Arcs excitation during ICRF operations

Example of a generic ICRF system (but all the same very similar to the ITER one)



Transmitters
+ Power supply

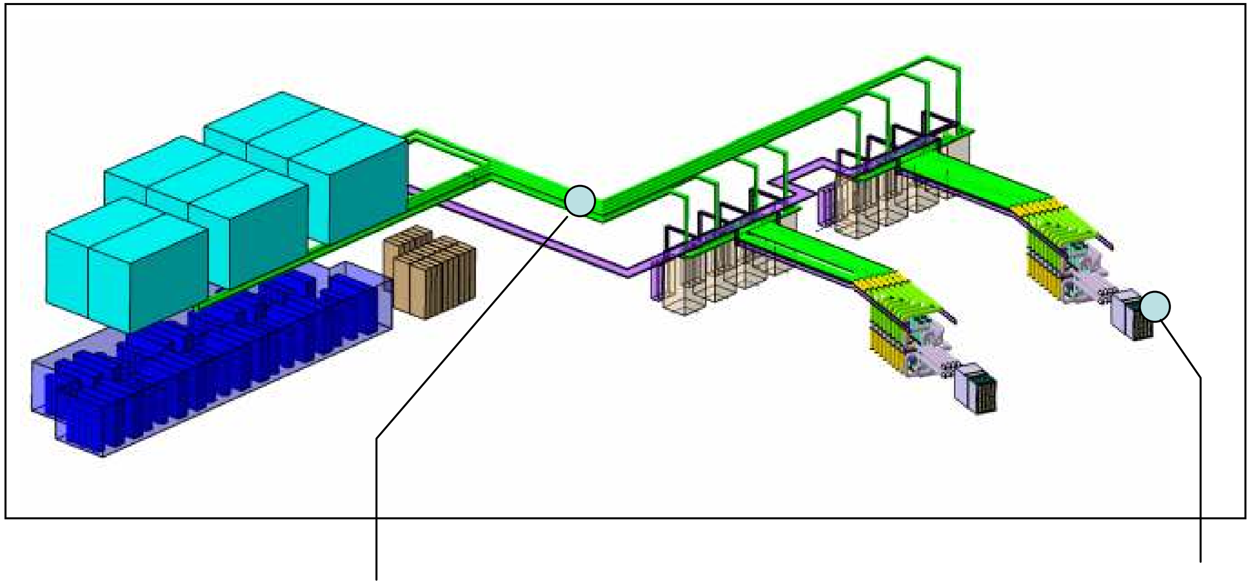
Transmission
lines

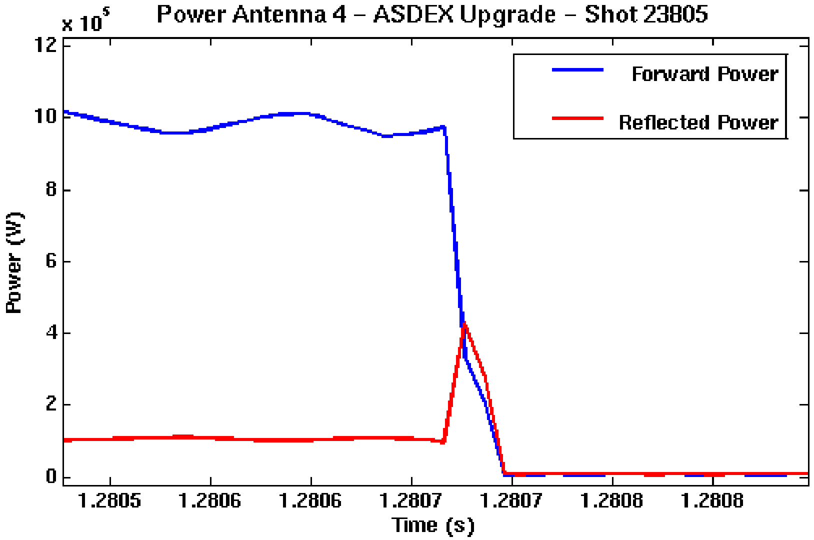
Matching system

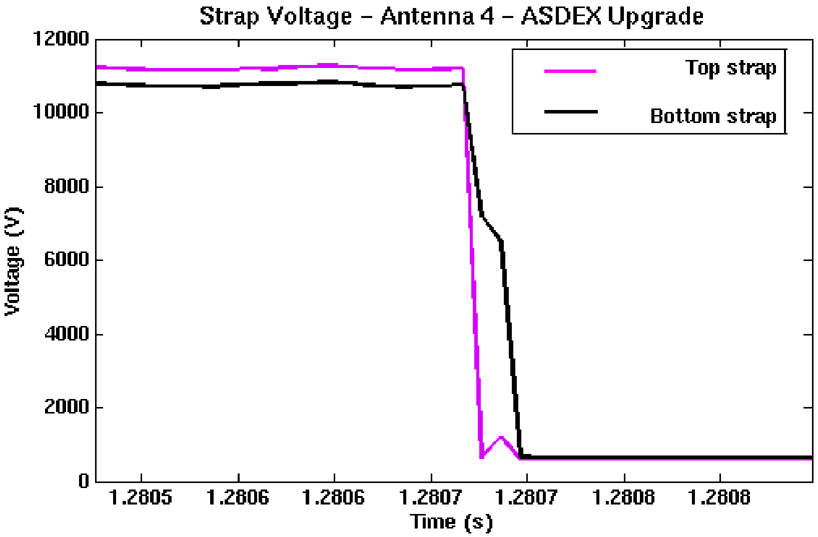
Antennas

Arcs excitation during ICRF operations

Brutal variation of RF parameters: increase of reflected power, drop of voltage

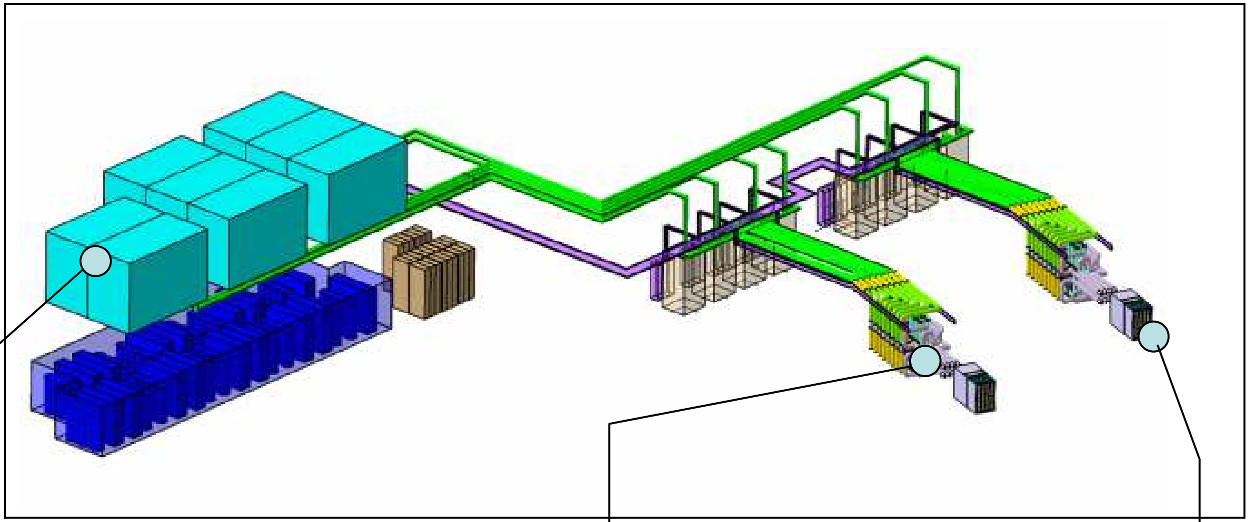




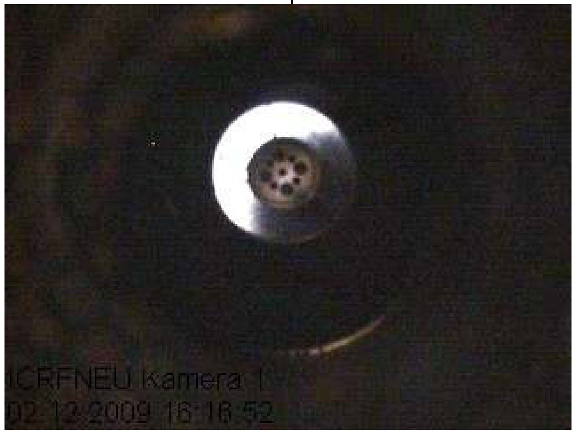


Arcs excitation during ICRF operations

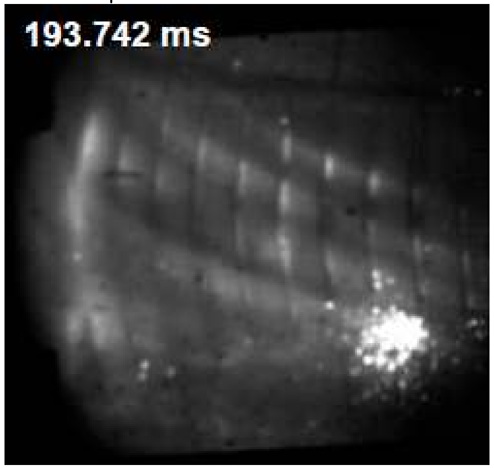
Video systems reveal flashes of light at the location of arc



Arc in generator of ASDEX Upgrade



Arc in Manipulator eXPeriment

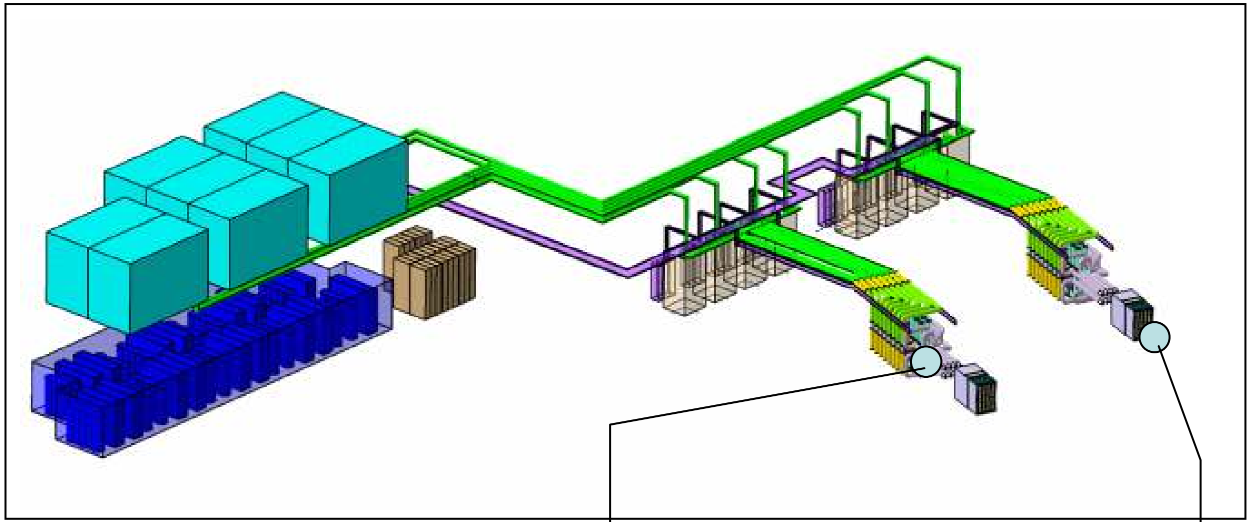


Antenna Alcator C-Mod

J. Caughman – Breakdown issues 2010

Arcs excitation during ICRF operations

Post-experiment inspection reveals damages ranging from surface erosion to leaks.



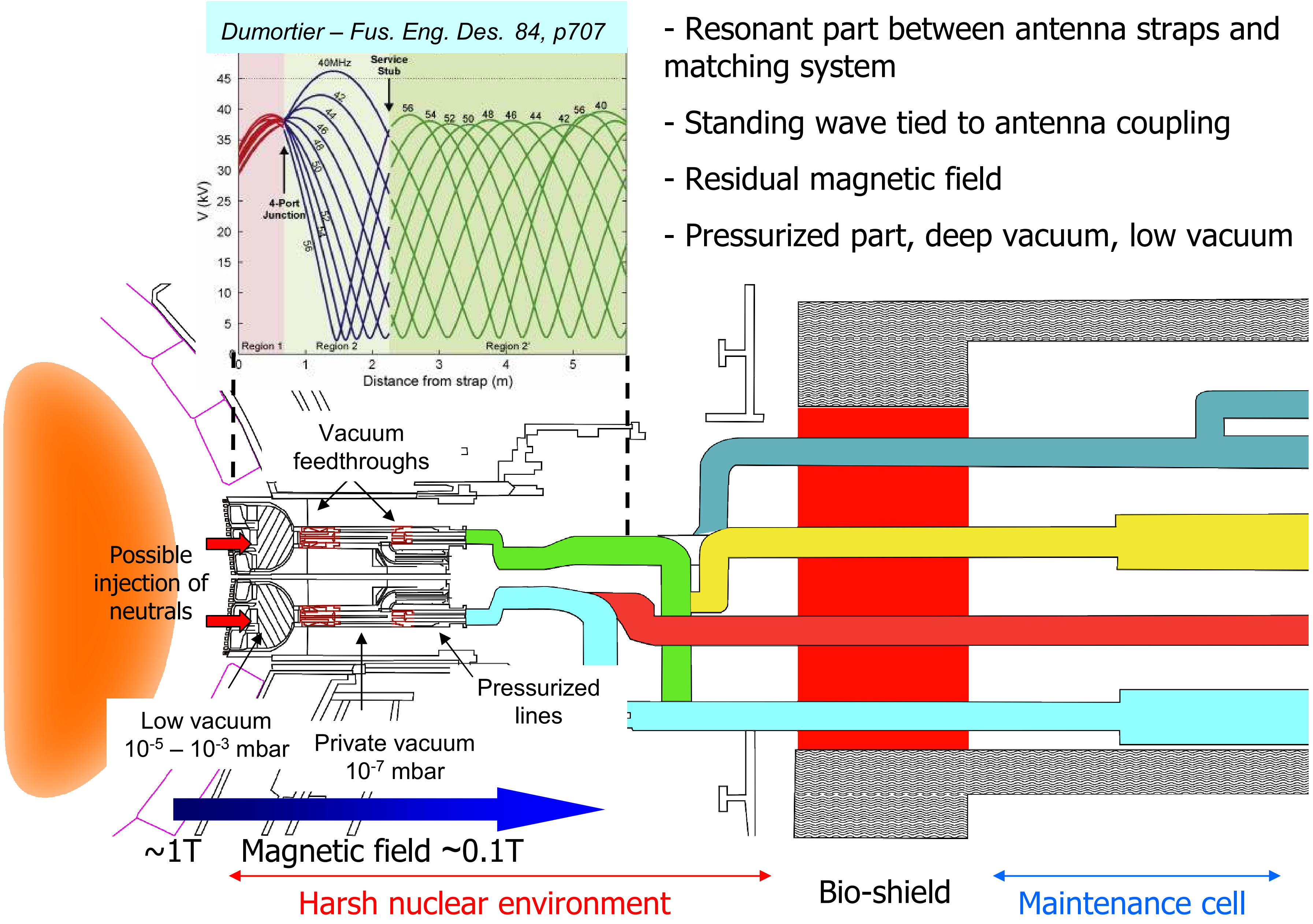
Punctured bellow – Manipulator eXPeriment (IPP)

Vacuum feedthrough – ASDEX Upgrade

Antenna feeder – ASDEX Upgrade

ICRF-specific environment for arcing

- Resonant part between antenna straps and matching system
- Standing wave tied to antenna coupling
- Residual magnetic field
- Pressurized part, deep vacuum, low vacuum


Dumortier – Fus. Eng. Des. 84, p707

~ Part 1 ~

Arcs 101

Largely inspired from the following works:

V. Bobkov, Studies of high voltage breakdown phenomena on ICRF antennas, PhD thesis

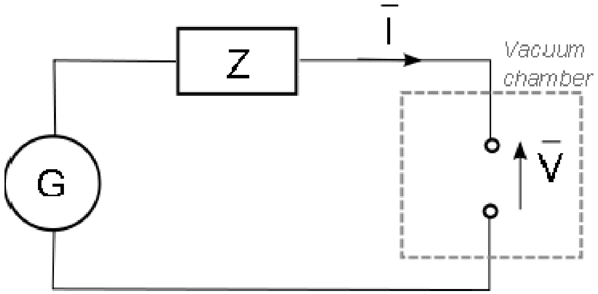
J. Caughman, Study of RF Breakdown Mechanisms Relevant to an ICH Antenna Environment, *AIP Conference Proceedings* 933 p. 195

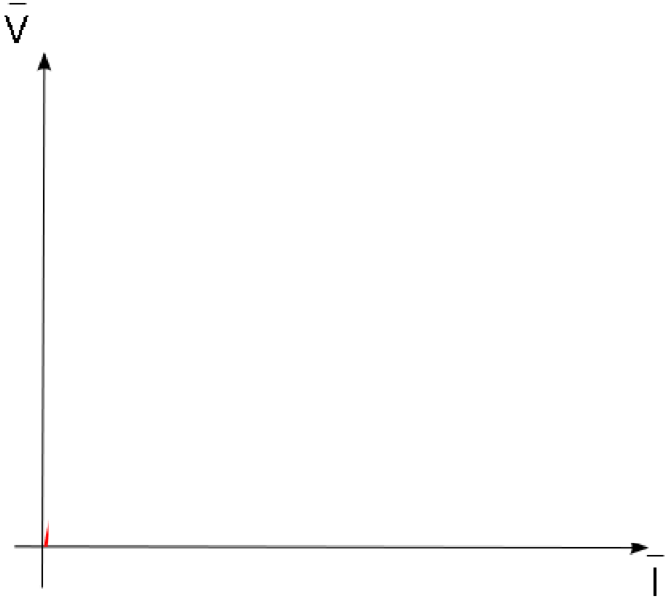
T.P. Graves, Experimental investigation of electron multipactor discharges at very high frequencies, PhD thesis

J. Norem – I-08 Modeling arcs – This conference

Characteristic phases of an arc

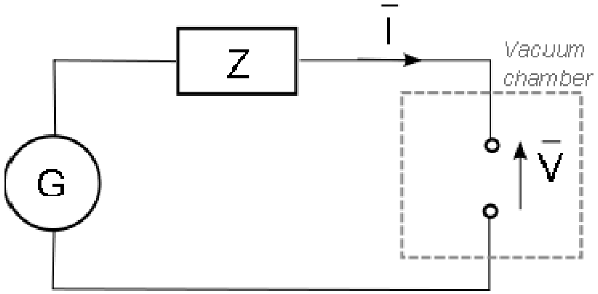
Determination of the voltage/Current evolution of the interelectrode volume





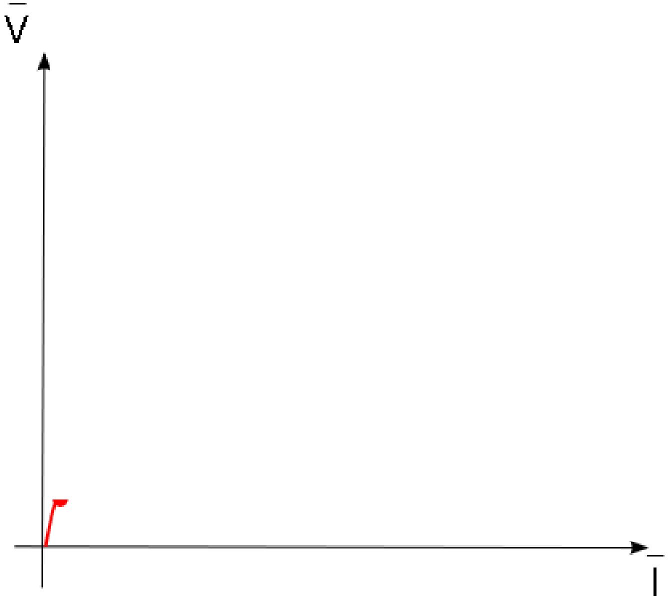
Characteristic phases of an arc

Determination of the voltage/Current evolution of the interelectrode volume



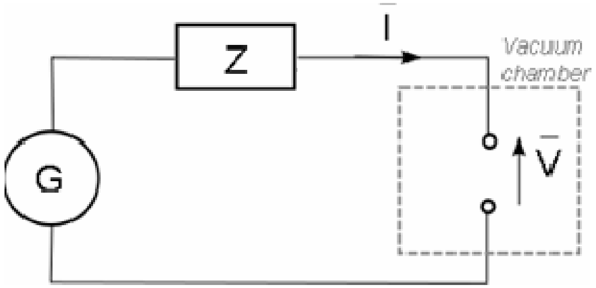
<u>1st step:</u> increase at low voltage

Vacuum insulation: no current



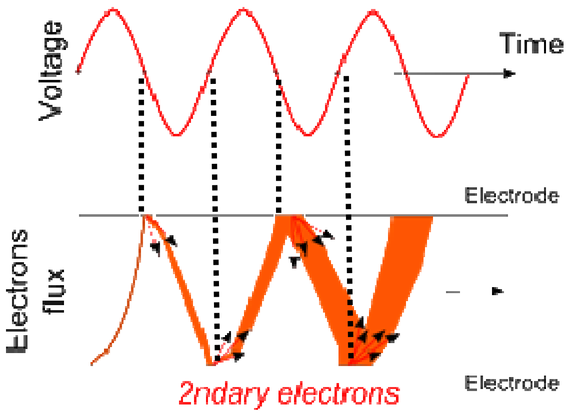
Characteristic phases of an arc

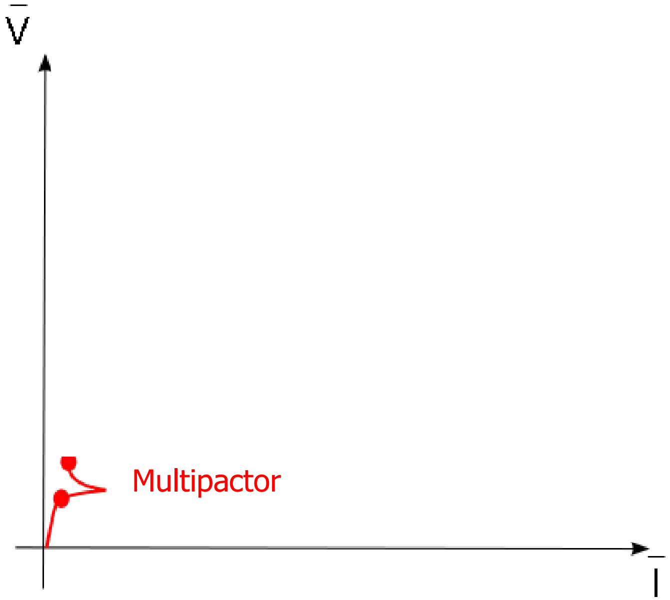
Determination of the voltage/Current evolution of the interelectrode volume



2nd step: development of multipactor

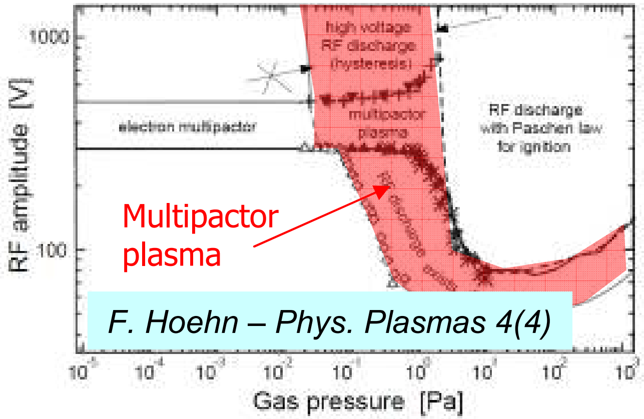
Electron avalanche caused by secondary electron emission when resonance between electron flight time and RF field cycle





A transition region exists where the pressure is low enough for multipactor to exist and trigger a RF discharge at low voltage

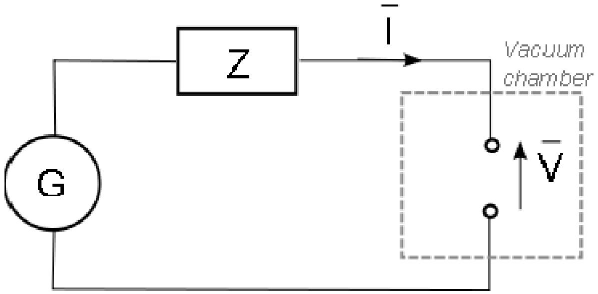
T.P. Graves – J. Vac. Sci. Tech A 24(3)

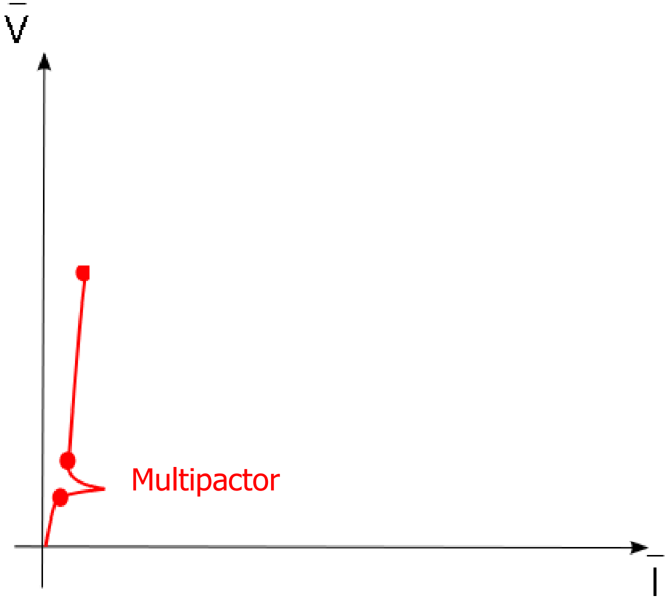


F. Hoehn – Phys. Plasmas 4(4)

Characteristic phases of an arc

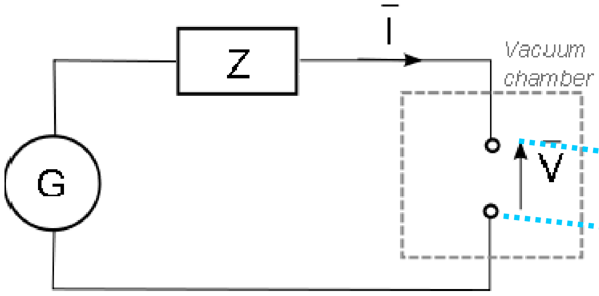
Determination of the voltage/Current evolution of the interelectrode volume





Characteristic phases of an arc

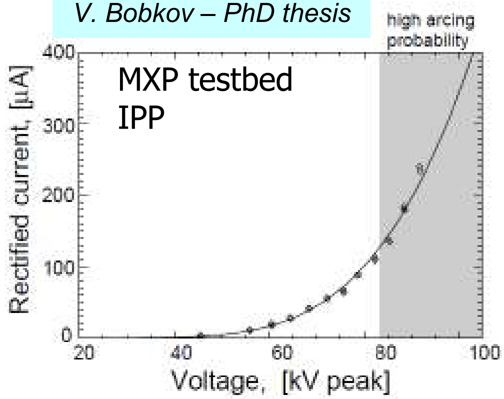
Detrmination of the voltage/Current evolution of the interelectrode volume

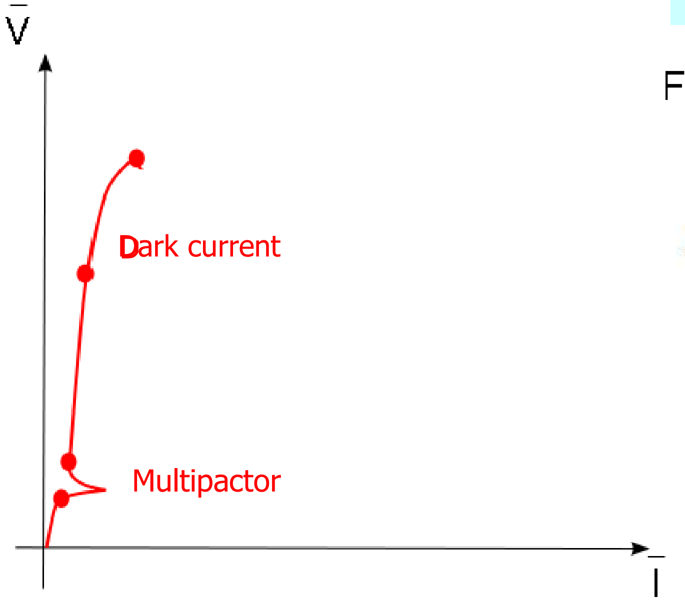


3rd step: dark current

Caughman – AIP 933, p 125

V. Bobkov – PhD thesis





Field Emission (~μA) given by Fowler-Nordheim law:

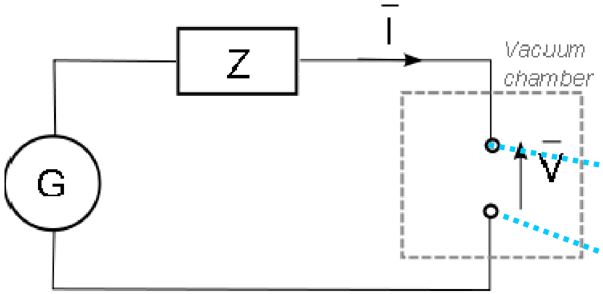
$$I_{RF} = A_{RF} \cdot \frac{M \cdot \beta_{RF}^{5/2} E_{RF}^{5/2}}{\phi^{7/4}} \cdot \exp\left(\frac{-6.83 \cdot 10^9 \phi^{3/2}}{\beta_{RF} E_{RF}}\right)$$

RH Fowler and LW Nordheim,
Proc Roy Soc A 119 (1928) p. 173

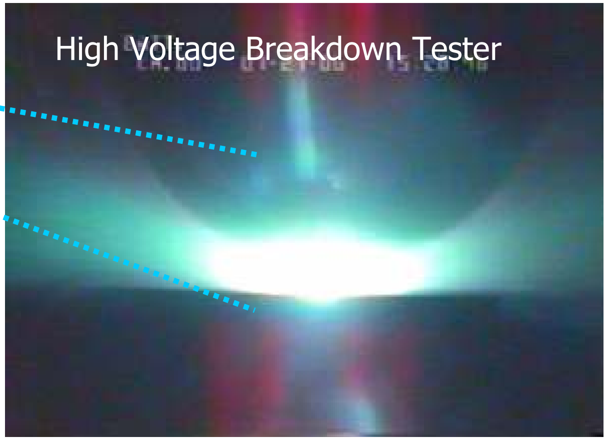
🟢 Geometry
🟤 Surface
🔵 Material
🔴 Voltage

Characteristic phases of an arc

Determination of the voltage/Current evolution of the interelectrode volume



4th step: sparking **Exact scenario not known**

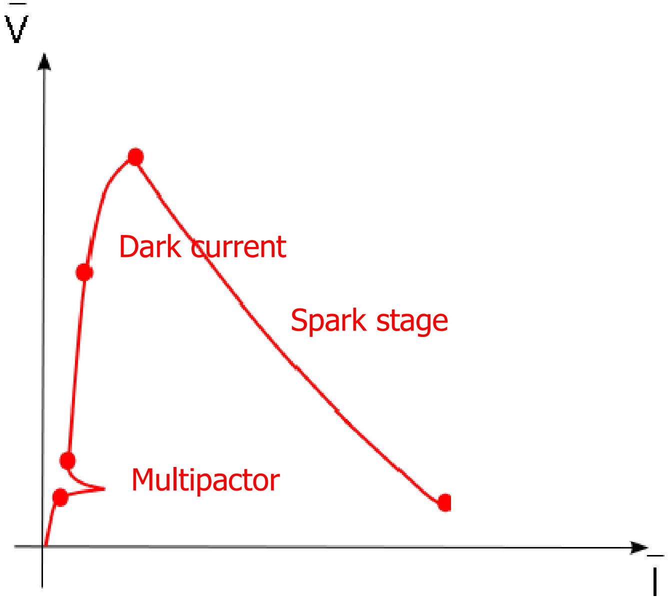


Caughman – AIP 933, p 125

- Field emission theory:

- Injection of electrons in interelectrode gaps by field emission
- Vaporization of emitting side by Joule heating or by electron bombardment

=> Growing conductance of the gap: breakdown



For idealized ICRH structures, theory yields: ~ GV.m^{-1}
Measurements give: ~ MV.m^{-1}.

Possibly enhanced emission due to protrusions, gas adsorption

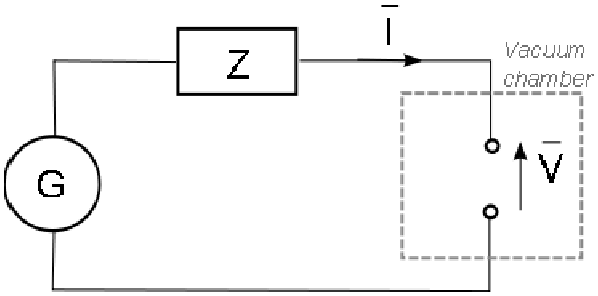
SJ Wukitch – Plasma Phys. Control. Fusion 46 1479

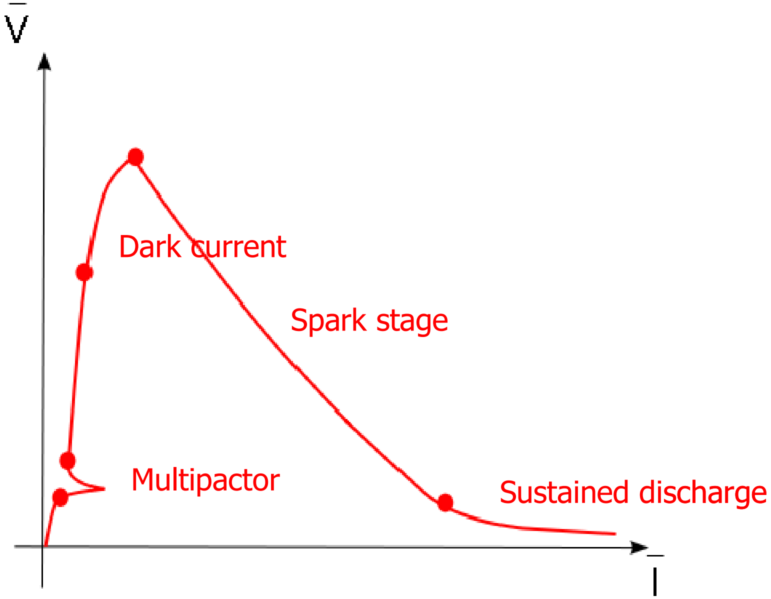
- Alternative scenario: “clump“ theory – acceleration of microparticles

L Cranberg, *J Appl Phys* **23** (1952), p. 518

Characteristic phases of an arc

Determination of the voltage/Current evolution of the interelectrode volume





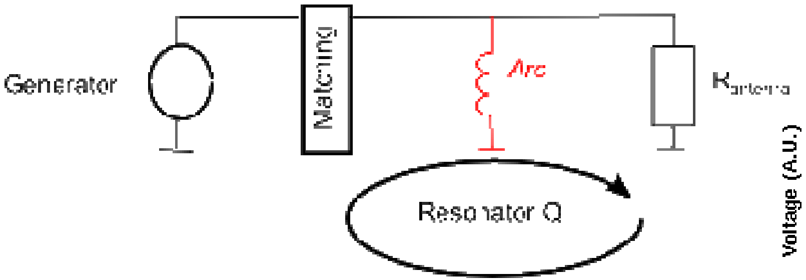
<u>4th step:</u> sustained discharge

Accessible if:

- external circuit delivers a current exceeding a critical value at a voltage high enough to sustain cathode spots;
- combined field-thermal electron emission is initiated from the cathode.

Reaction of ICRF System to arcing

A broad range of loads may be used as simple electrode gap. The initiation of an arc will thus change the tuning of the ICRF system which will in turn change the boundary conditions of the arc: very fast transient.



Different time scales:

a) Arc initiation: ~ 10^{-8} s

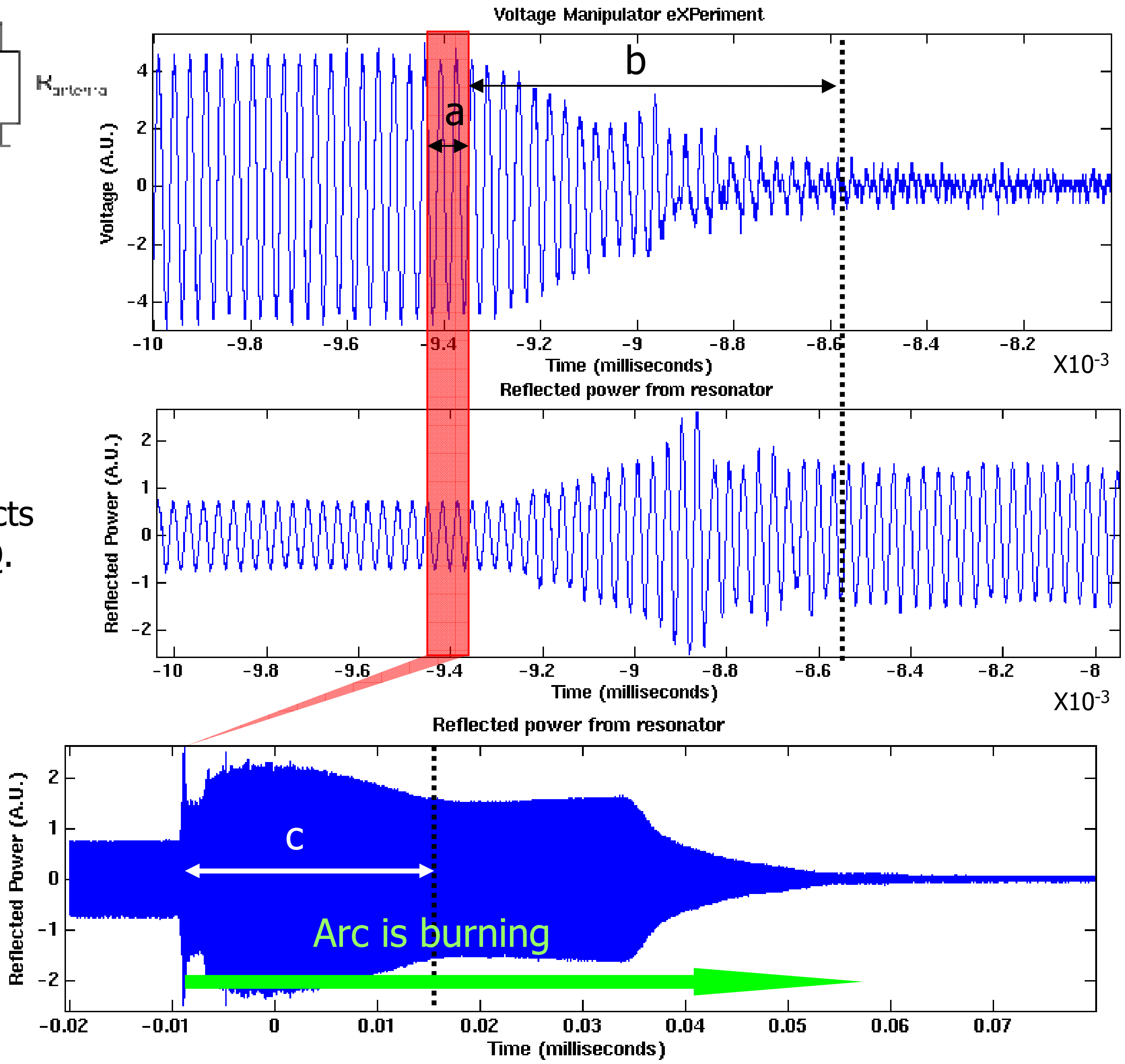
b) Detuning of resonator: ~ 10^{-7} s

The unmatched part of the system acts as a resonator with a quality factor Q. Its stored energy is released in arc, detuning the matching system:

-Voltage in the resonator drops

- **<u>Reflected power towards generator increases</u>**

c) Reaction of generator: ~ 10^{-3} s

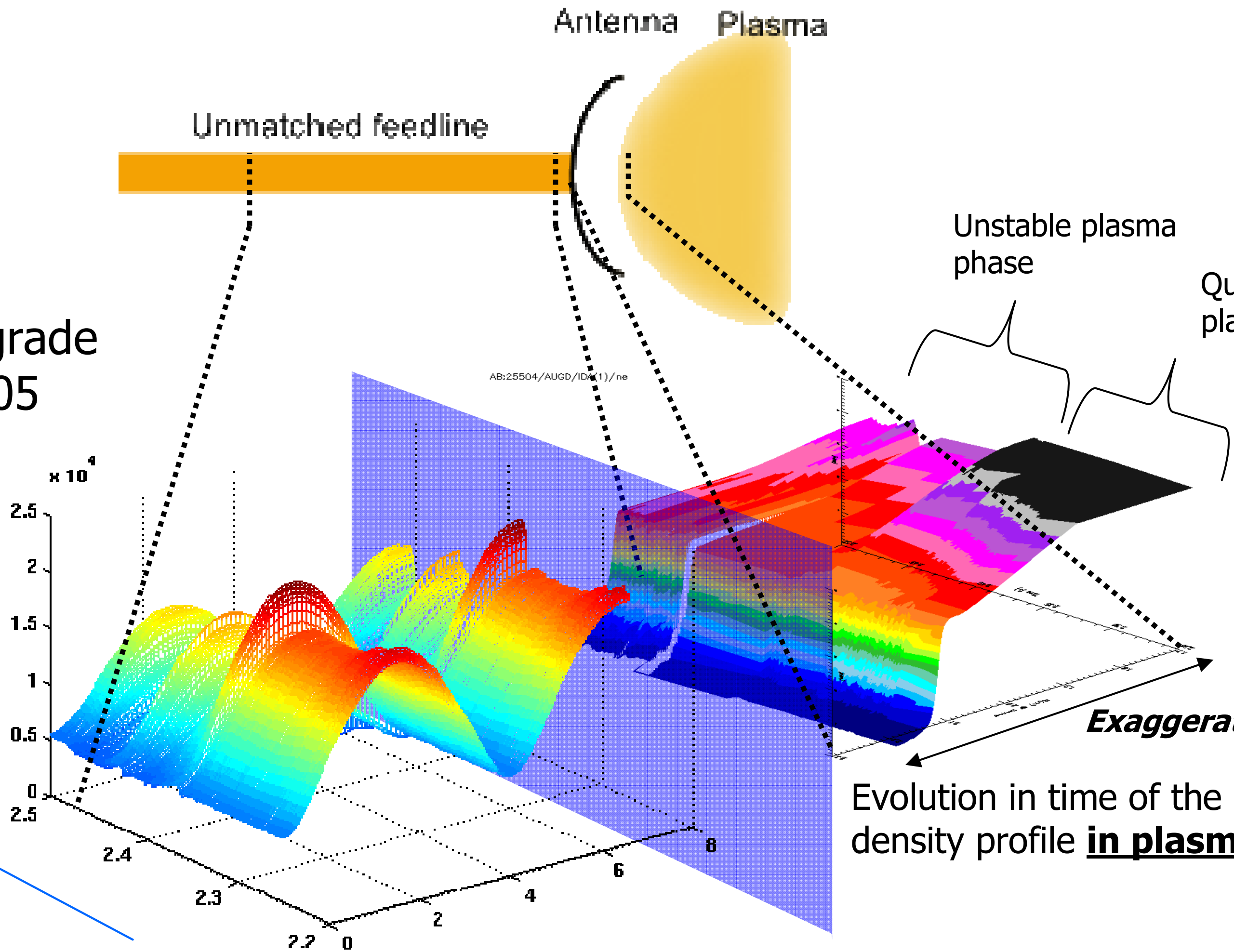


~ Part 2 ~

Arc detection: the traditional way

Detection based on the amplitude of the reflection coefficient or VSWR

Problem A: system reaction to plasma instabilities



ASDEX Upgrade
Shot #23805

Unstable plasma
phase

Quiescent
plasma phase

Exaggerated axis

Evolution in time of the edge density profile **in plasma**

Time
evolution

Evolution in time of the voltage profile **in transmission line**

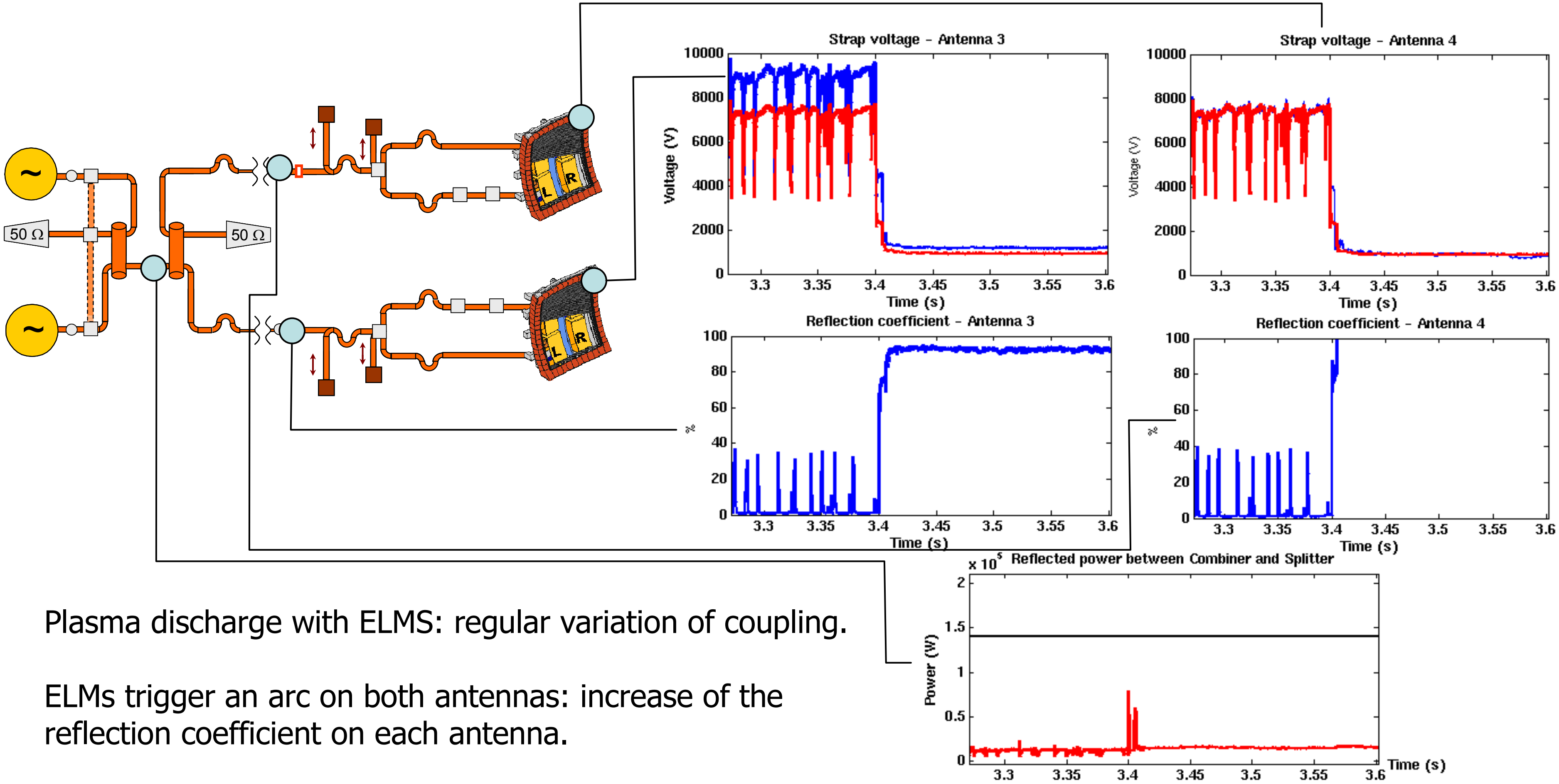
Antenna

AUG Standing Wave Fitting – I. Stepanov

Problem A: system reaction to plasma instabilities

ICRF systems are hardened to operate during plasma instabilities

Example of 3dB splitter ELM resilience on ASDEX Upgrade and problem for arcs



Plasma discharge with ELMS: regular variation of coupling.

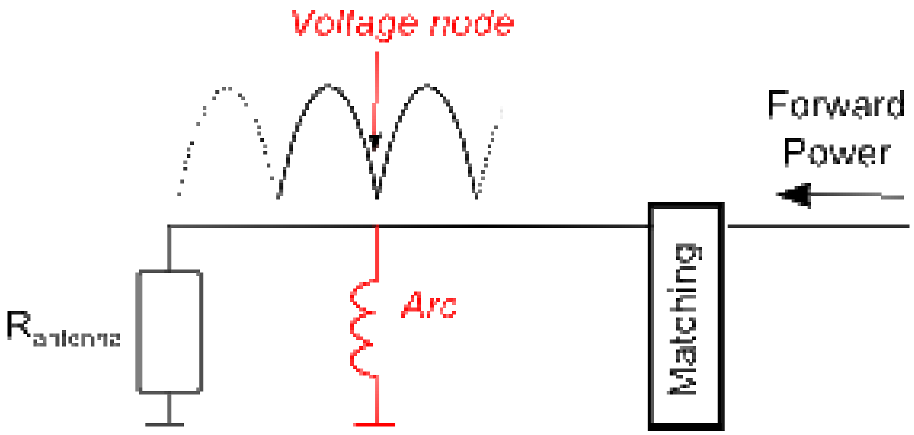
ELMs trigger an arc on both antennas: increase of the reflection coefficient on each antenna.

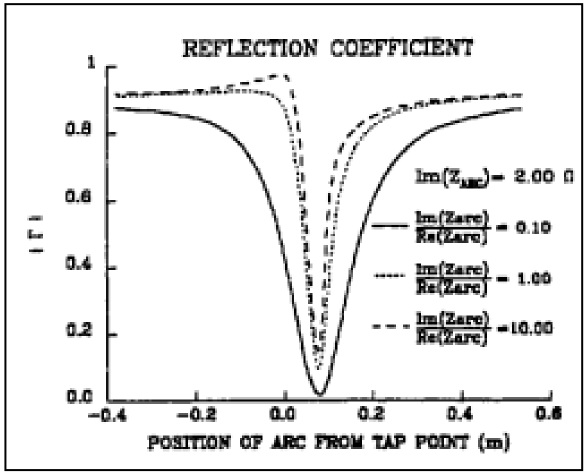
The ELM-resilience system cancel the effect of both arcs on the detector

Typical symmetric fault also observed on DIII-D in balanced feed configuration

Problem B: “ghost“ arcs aka low-voltage arcs

Existence anticipated by J. Caughman in 1994: arcs with higher impedance than the local impedance of the RF system.

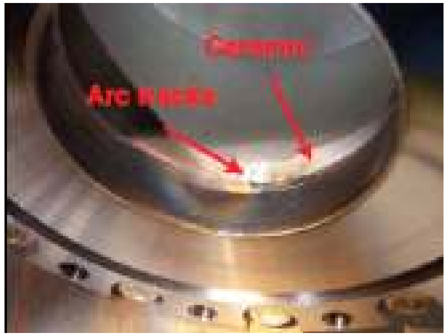




Caughman, AIP 289, p279

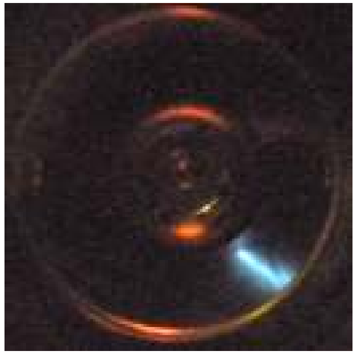
There are inconspicuous arcs: little impact on the RF parameters (VSWR, reflected power).
=> Therefore very difficult to detect

Many examples identified on different machines:



Vacuum window – DIII-D

A2 Bellow - JET



Observation on Vacuum window - MXP

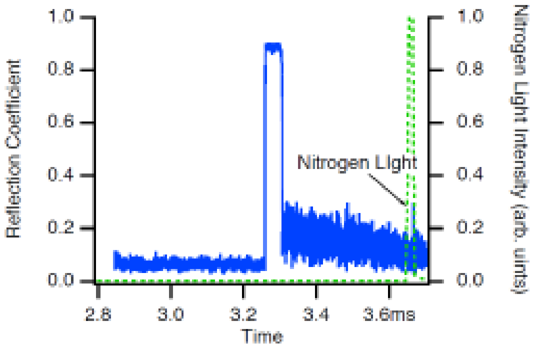
Problem B: “ghost“ arcs

The nature of these arcs is not identified and is probably not unique.
Multipactor and multipactor-induced discharge could be a key factor.
These arcs occur at very different locations but are all inconspicuous (at different degrees)

I. Monakhov,AIP, 933 (151)

Arcs on vacuum feedthrough

DIII-D, LHD, ASDEX Upgrade, testbed MXP



Not at voltage maximum.
Complex geometry.
Possible multipactor discharge, enhanced by degassing from walls.
Role of generator harmonics?

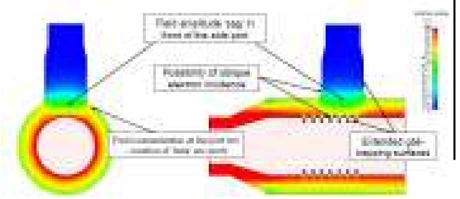
Arcs at voltage nodes

JET - A2 antenna Vacuum Transmission line

Tore Supra – ITER like antenna - capacitor

K. Vulliez, Fus. Engin. & Design 74 (267)

Complex geometry
Maximum current locations



Arcs on antennas

DIII-D, ASDEX Upgrade, Alcator C-Mod

Effect of ELMs: symmetric fault on DIII-D
Bursts of neutrals on antennas
+ Ionization
Possible multipactor discharge
Possible capacitive discharge
Effect of magnetic field

Short-circuits

Problems of grounding, generation of series arcs

1 DC-break lost on MXP testbed

Surface arcs

Conclusion

VSWR-based detectors cannot detect “ghost” arcs and discriminate with difficulty high-voltage arcs from plasma instabilities

Yet, there are still in use on all machines.

Required to protect the transmitters from the reflected power: ultimate barrier

Very good and cheap tool to diagnose particular events inside the ICRF system.

~ Part 3 ~

Advanced detectors

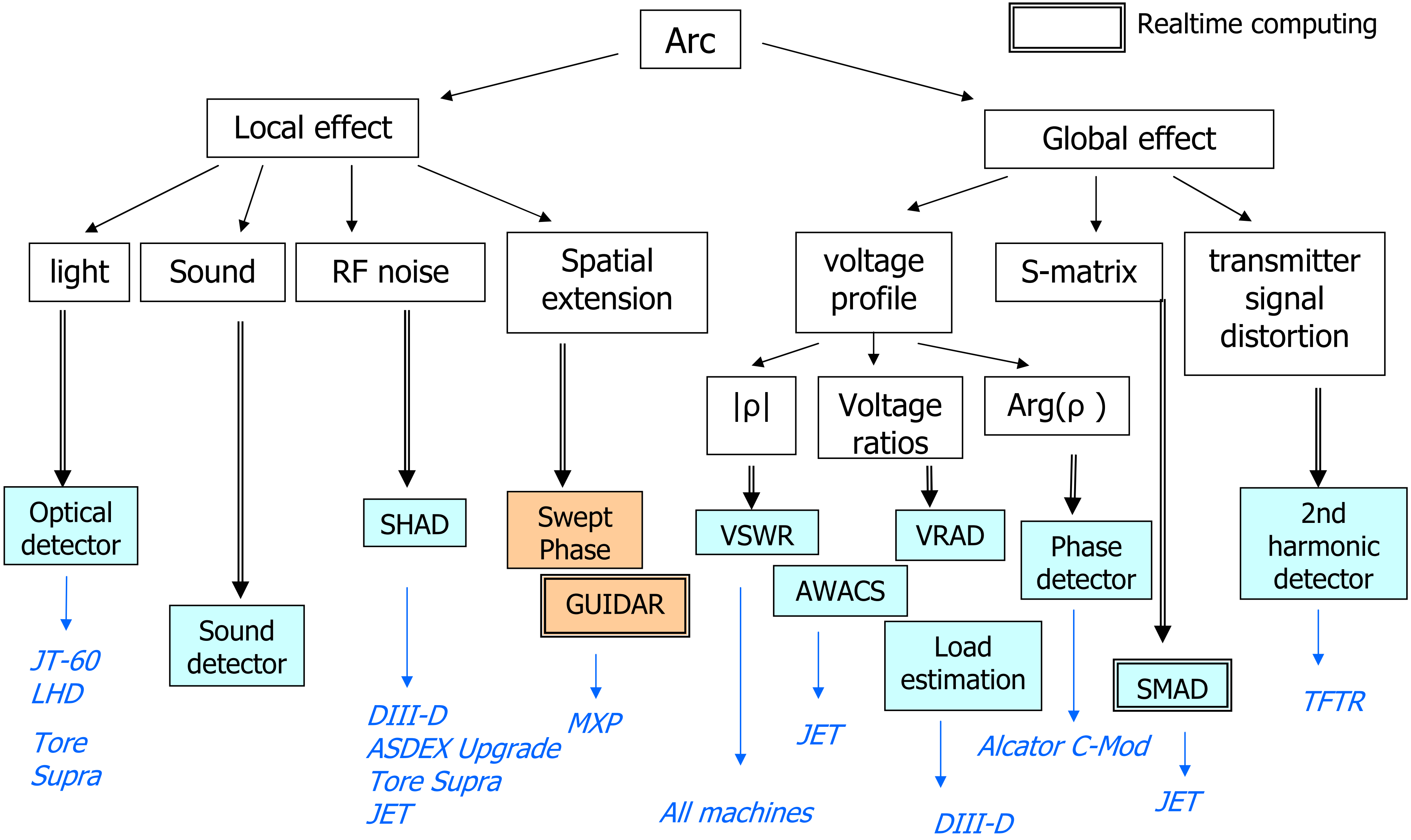
Phase, S-Matrix, Noise, Light and others

Family tree

🟦 Passive detector

🟧 Active detector

☐ Realtime computing



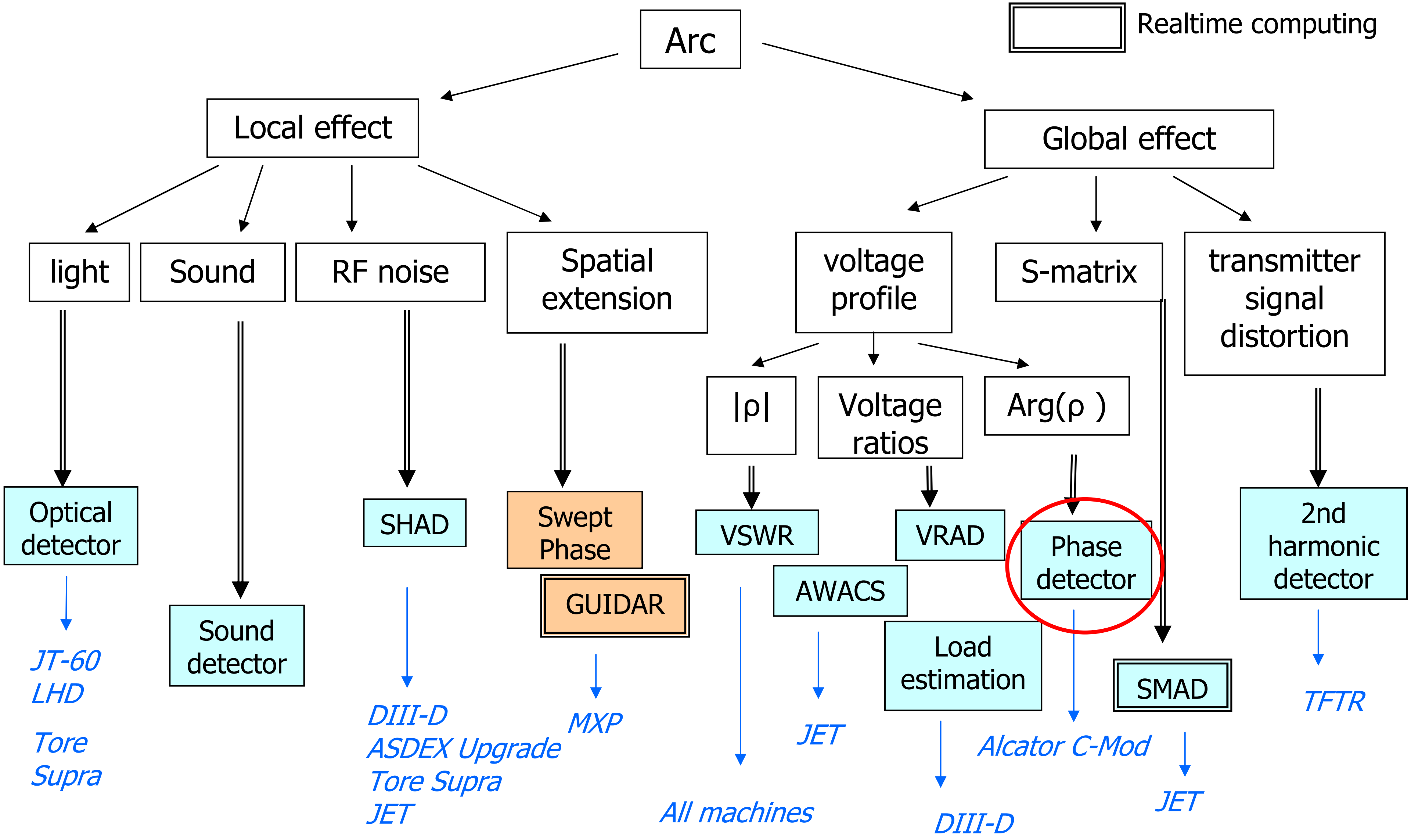
- Arc
  - Local effect
    - light
      - Optical detector
        - *JT-60*
        - *LHD*
        - *Tore Supra*
    - Sound
      - Sound detector
    - RF noise
      - SHAD
        - *DIII-D*
        - *ASDEX Upgrade*
        - *Tore Supra*
        - *JET*
    - Spatial extension
      - Swept Phase
      - GUIDAR
        - *MXP*
  - Global effect
    - voltage profile
      - |ρ|
        - VSWR
          - *All machines*
        - AWACS
          - *JET*
      - Voltage ratios
        - VRAD
        - Load estimation
          - *DIII-D*
      - Arg(ρ)
        - Phase detector
          - *Alcator C-Mod*
    - S-matrix
      - SMAD
        - *JET*
    - transmitter signal distortion
      - 2nd harmonic detector
        - *TFTR*

Family tree

🟦 Passive detector

🟧 Active detector

▭ Realtime computing



Arc

Local effect

Global effect

light

Sound

RF noise

Spatial extension

voltage profile

S-matrix

transmitter signal distortion

|ρ|

Voltage ratios

Arg(ρ)

Optical detector

JT-60
LHD

Tore
Supra

Sound detector

SHAD

DIII-D
ASDEX Upgrade
Tore Supra
JET

Swept Phase

GUIDAR

MXP

VSWR

All machines

AWACS

JET

VRAD

Load estimation

DIII-D

Phase detector

Alcator C-Mod

SMAD

JET

2nd harmonic detector

TFTR

Phase measurement

Purpose: gain one more measurement to distinguish arcs from plasma instabilities: information on both the real and imaginary part of the impedance at the origin of the detuning

Advantage: sensitive measurement.

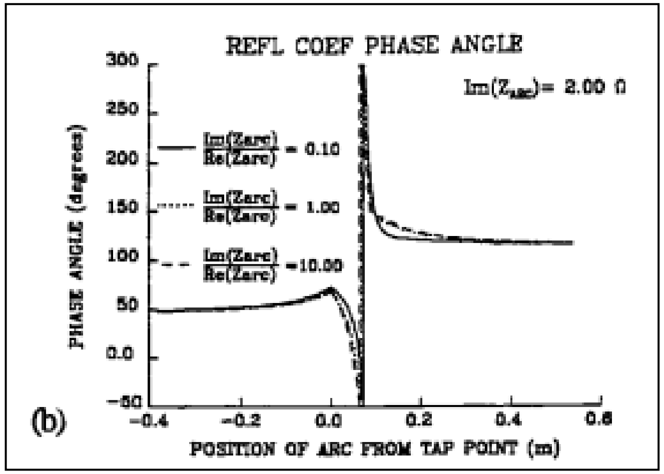
Good success on Alcator C-Mod although difficult to demonstrate discrimination of ELMS

P.T. Bonoli, Fus. Sci. & Techno. 51 (401)

Can phase detectors detect "ghost" arcs?

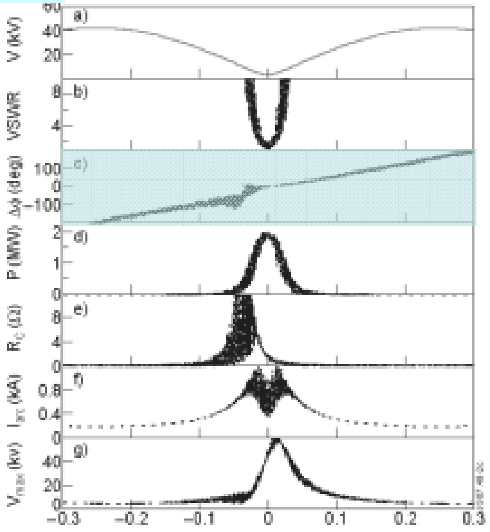
YES

Caughman, AIP 289, p279



NO

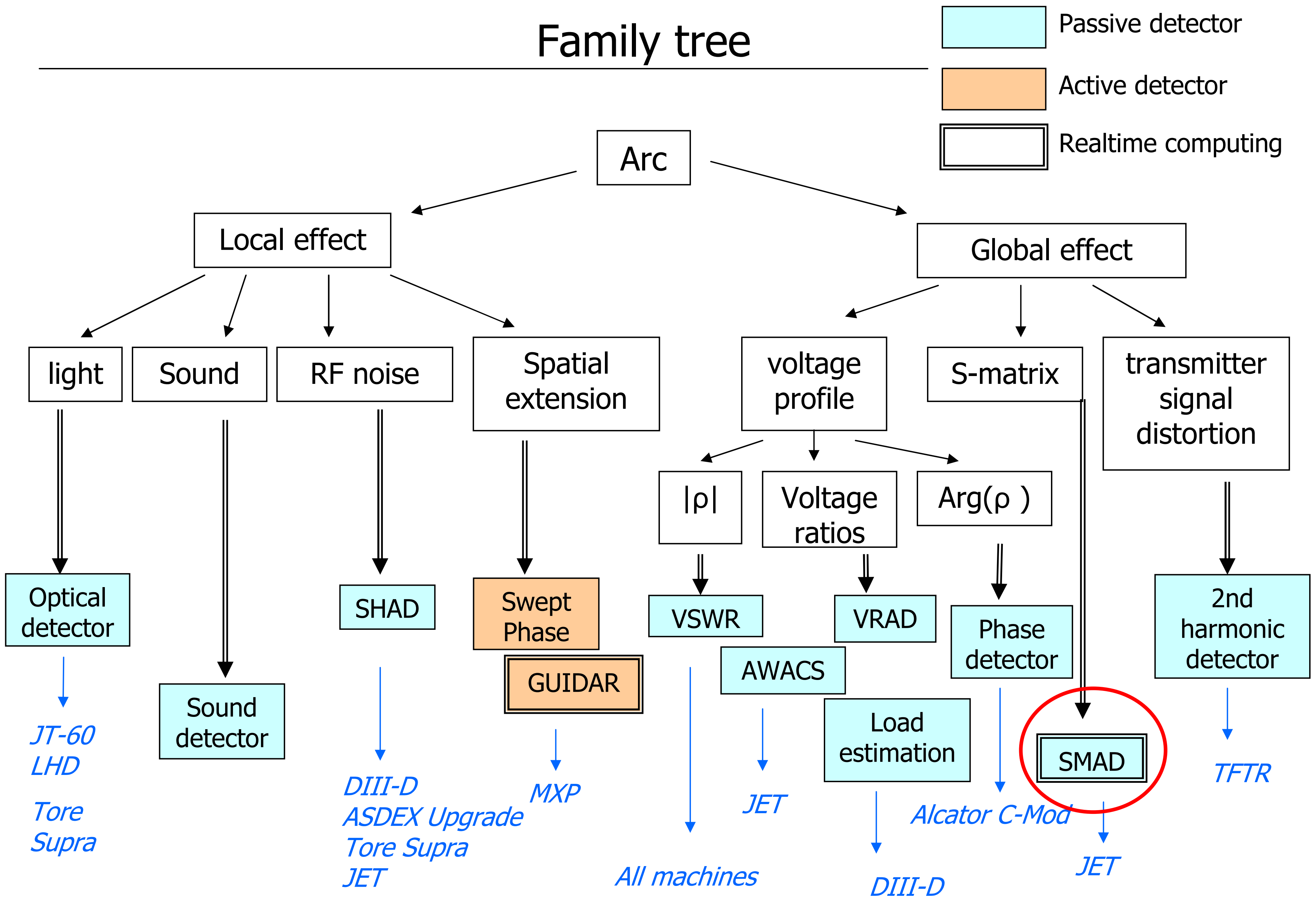
I. Monakhov,AIP, 933 (151)



It depends on the model of "ghost" arc and on the configuration of the RF system
=> analysis of phase pattern relative to arc type ongoing on DIII-D

T. Abrams, APS 2008

Family tree

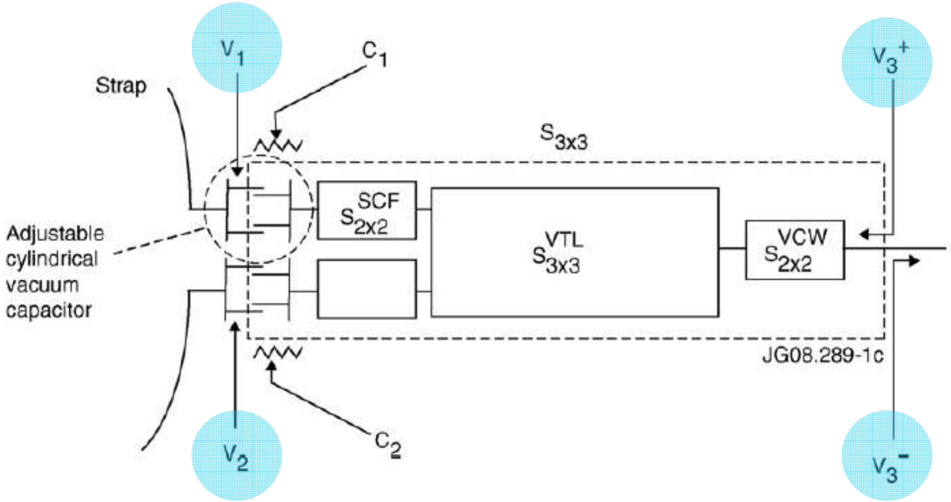

Passive detector
Active detector
Realtime computing
Arc
Local effect
Global effect
light
Sound
RF noise
Spatial extension
voltage profile
S-matrix
transmitter signal distortion
|ρ|
Voltage ratios
Arg(ρ)
Optical detector
Sound detector
SHAD
Swept Phase
GUIDAR
VSWR
AWACS
VRAD
Load estimation
Phase detector
SMAD
2nd harmonic detector
JT-60
LHD
Tore Supra
DIII-D
ASDEX Upgrade
Tore Supra
JET
MXP
All machines
JET
DIII-D
Alcator C-Mod
JET
TFTR

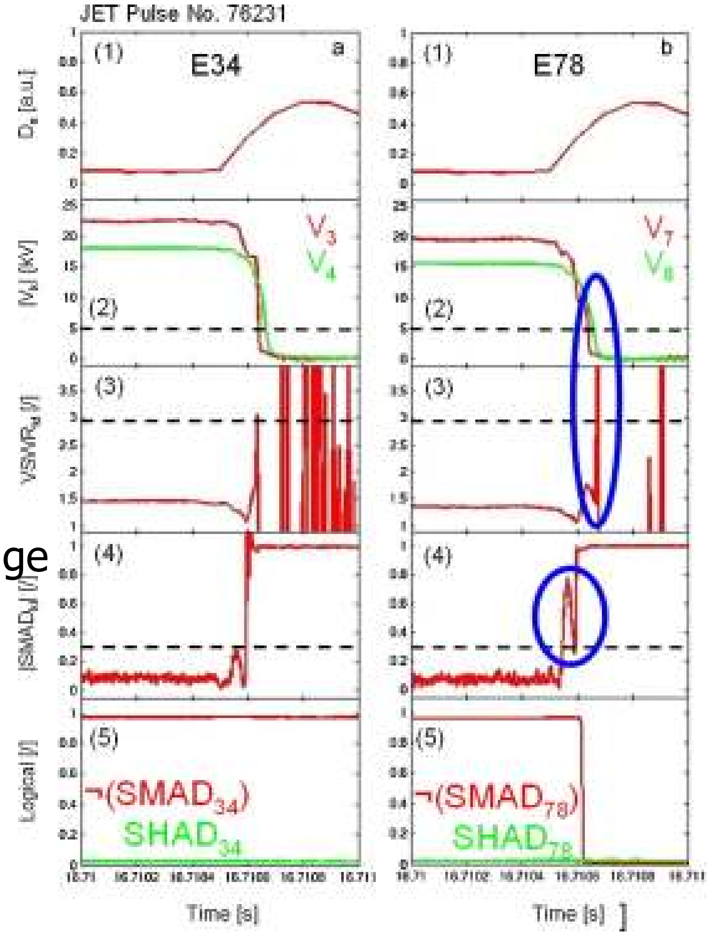
S-Matrix Arc Detector SMAD: the “ghost chaser”

VSWR, phase detectors are based on the comparison of two or three measurements with a 1D model of the ICRF system.

The SMAD takes 4 measurements and compare them with a 3D model of Capacitors(+bellows)+T-junction+VTL+VCW of the ILA antenna on JET

M. Vrancken, Fusion Eng. & Design





⇒ Encouraging signs of successful detection of low voltage arcs at T-junction

⇒ Commissioning:

- Protracted/challenging (“during” ~560 pulses)
- 500MB/shot, ~160 Pulses SMAD operational

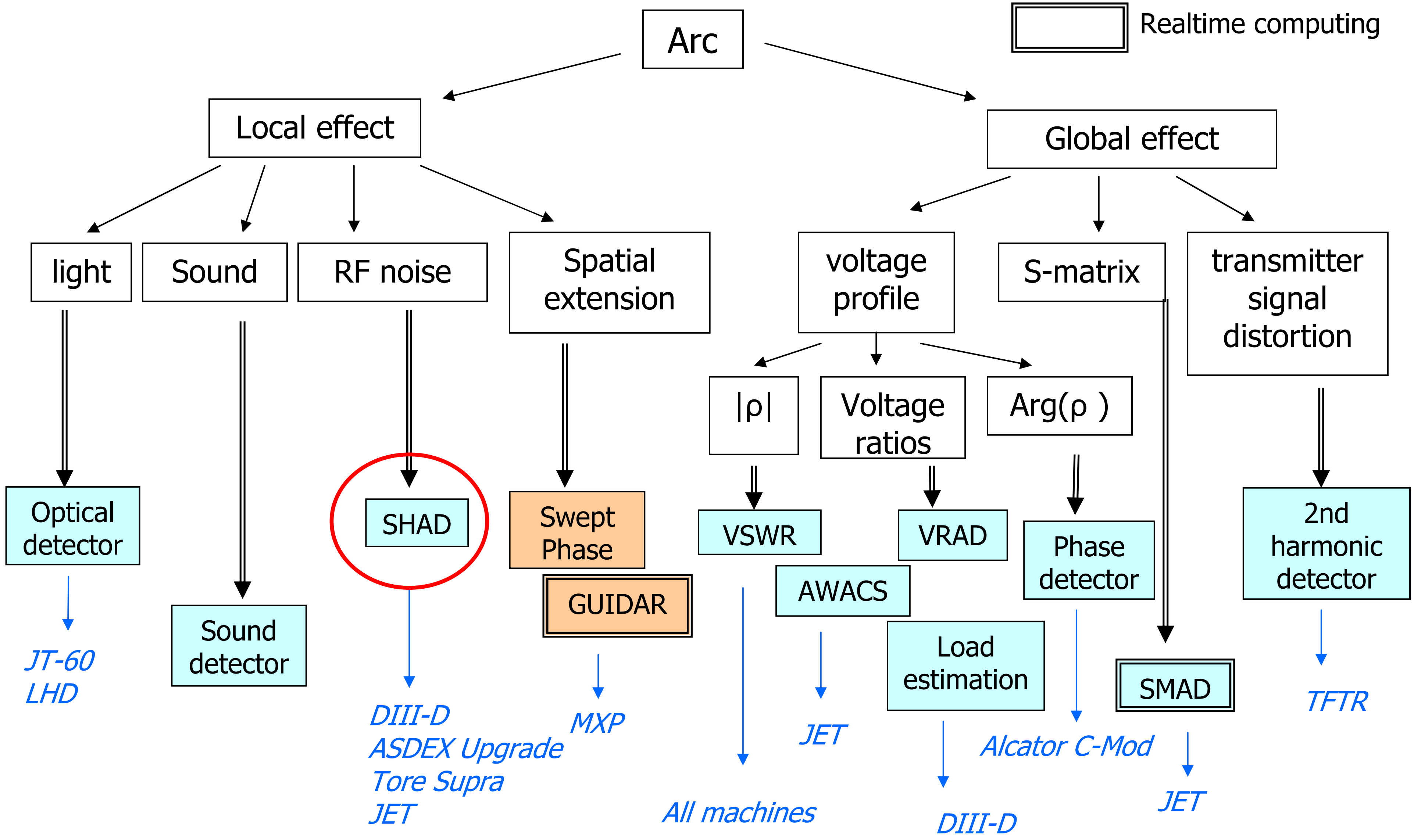
⇒ System specific RF models, accuracy achievable ?

Family tree

🟦 Passive detector

🟧 Active detector

▭ Realtime computing



Arc

Local effect

- light
  - Optical detector
    - JT-60
    - LHD
- Sound
  - Sound detector
- RF noise
  - SHAD
    - DIII-D
    - ASDEX Upgrade
    - Tore Supra
    - JET
- Spatial extension
  - Swept Phase
  - GUIDAR
    - MXP

Global effect

- voltage profile
  - |ρ|
    - VSWR
      - All machines
    - AWACS
      - JET
  - Voltage ratios
    - VRAD
    - Load estimation
      - DIII-D
  - Arg(ρ)
    - Phase detector
      - Alcator C-Mod
- S-matrix
  - SMAD
    - JET
- transmitter signal distortion
  - 2nd harmonic detector
    - TFTR

Sub Harmonic Arc Detector SHAD: detection of RF noise

During the spark phase, a current breaks the vacuum down in a few nanoseconds.

This corresponds to the excitation of frequencies up to several hundreds of MHz.

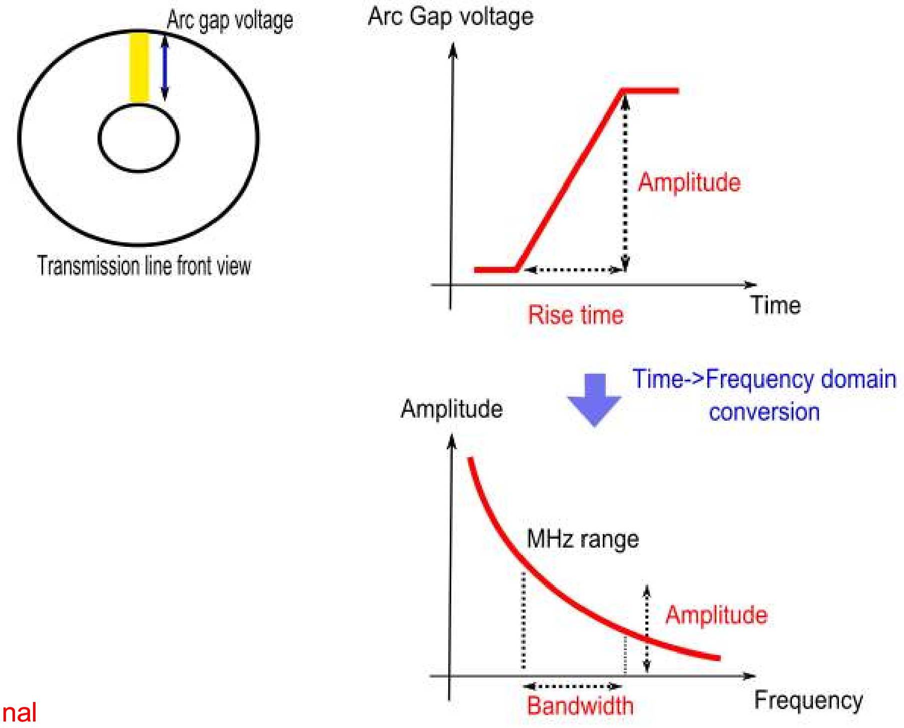
While burning, the arc lights cathode spots on and off, creating a brown noise.

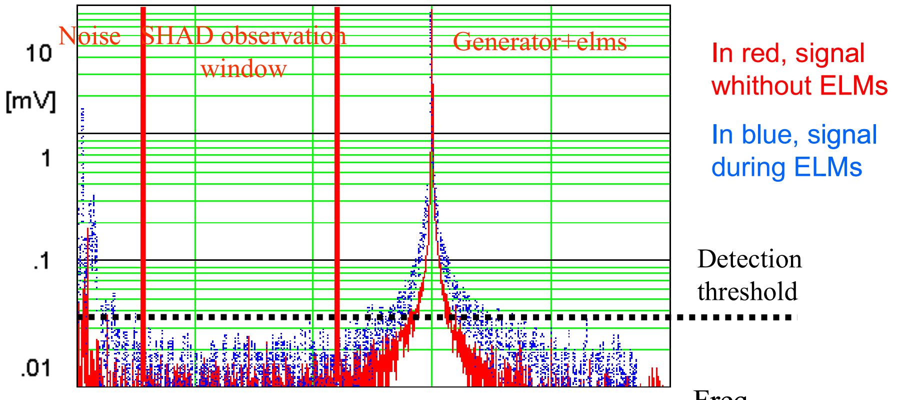
J.H. Rogers, 16th SOFE

D.A. Phelps, AIP 403 (401)

F. Braun, SOFT 1996

G. Berger-By AIP 933, p211





typical ICRF line voltage spectrum

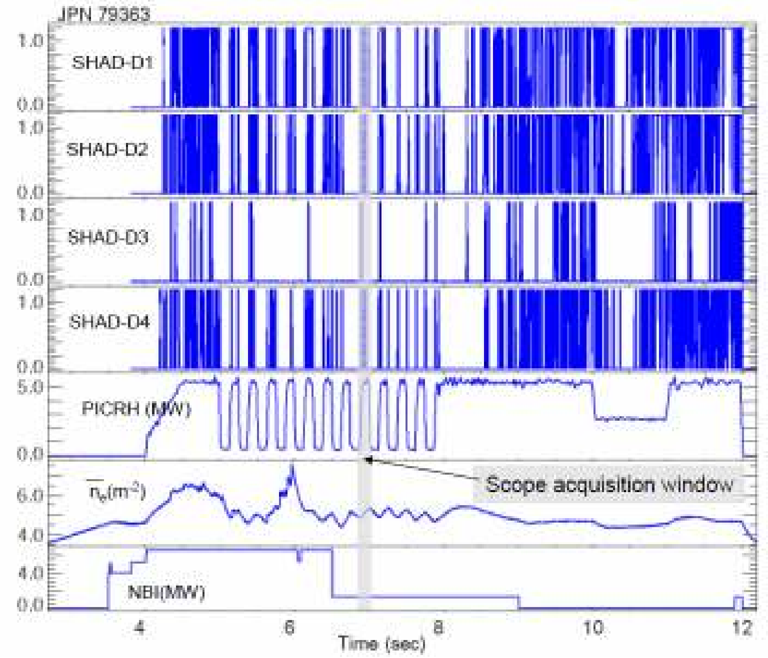
The SHAD is based on a filter that rejects the signal from the transmitter and the low frequency noise, to detect only noise from the arc.

Arc frequencies are captured in this window and above a given threshold, the detection is triggered.

SHAD: problem of spurious detections

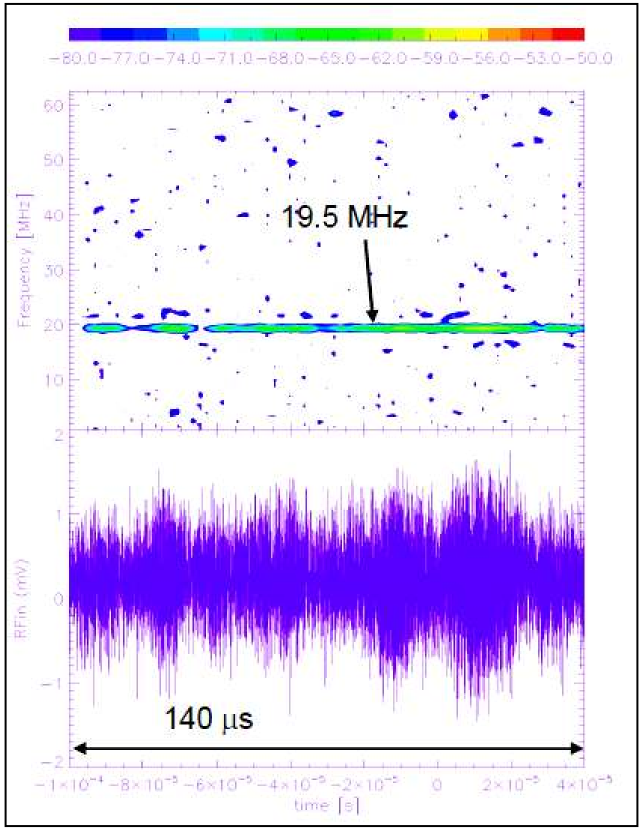
Example on JET

79363, 2.62 Tesla (^{3}He)H plasma, ICRH freq=51 MHz



Numerous detections, not confirmed by other detectors.

Spectrogram of the voltage probe signal used by the SHAD. Frequency corresponds to He3 cyclotron emission at the edge



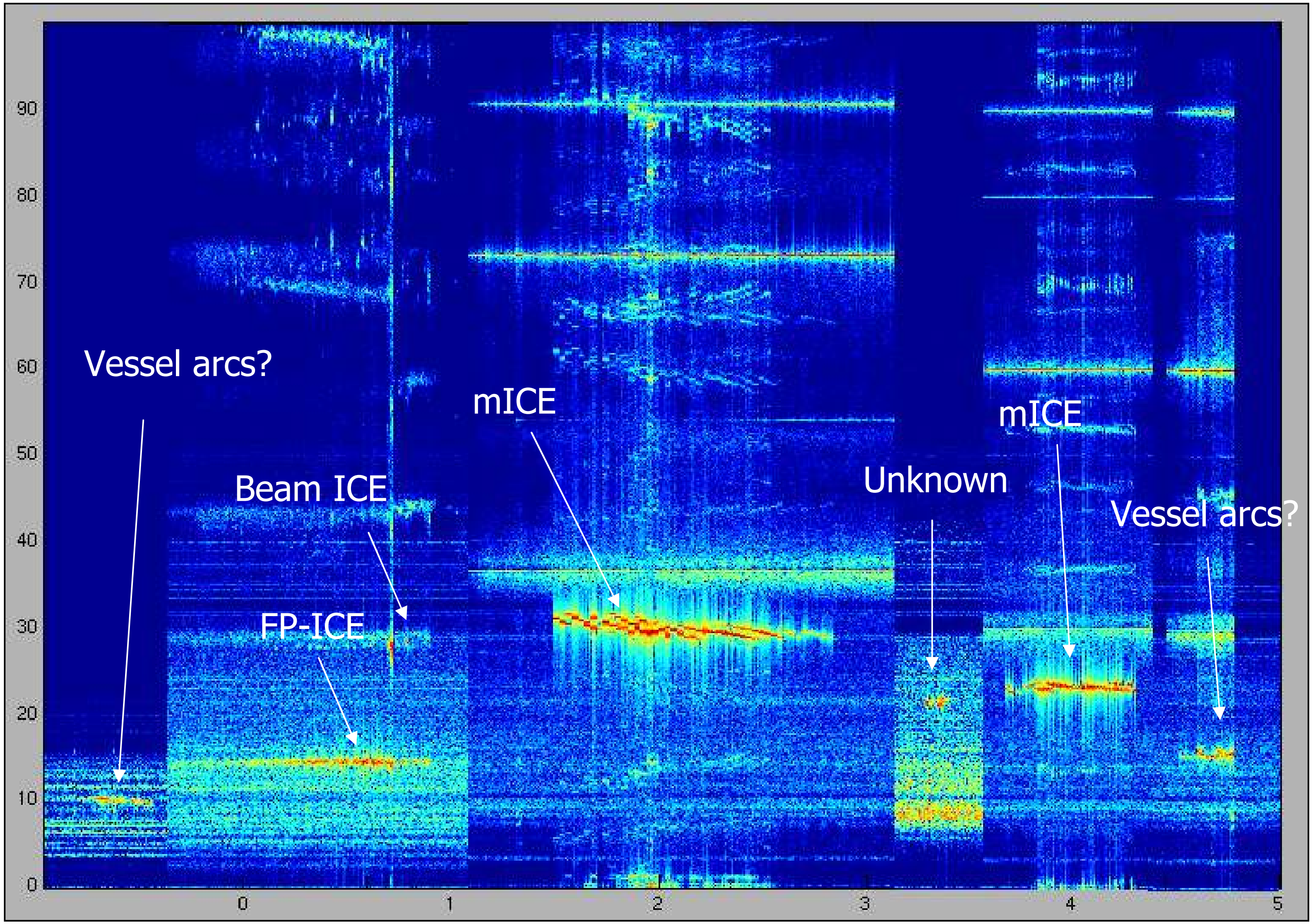
Ion Cyclotron Emission (ICE) main candidate as origin of spurious detections; observed on JET, DIII-D, ASDEX-Upgrade, TFTR, JT-60U.

But not the only one: SHAD observe during ELMs on JET and ASDEX Upgrade frequencies (~10MHz) lower than cyclotron frequencies

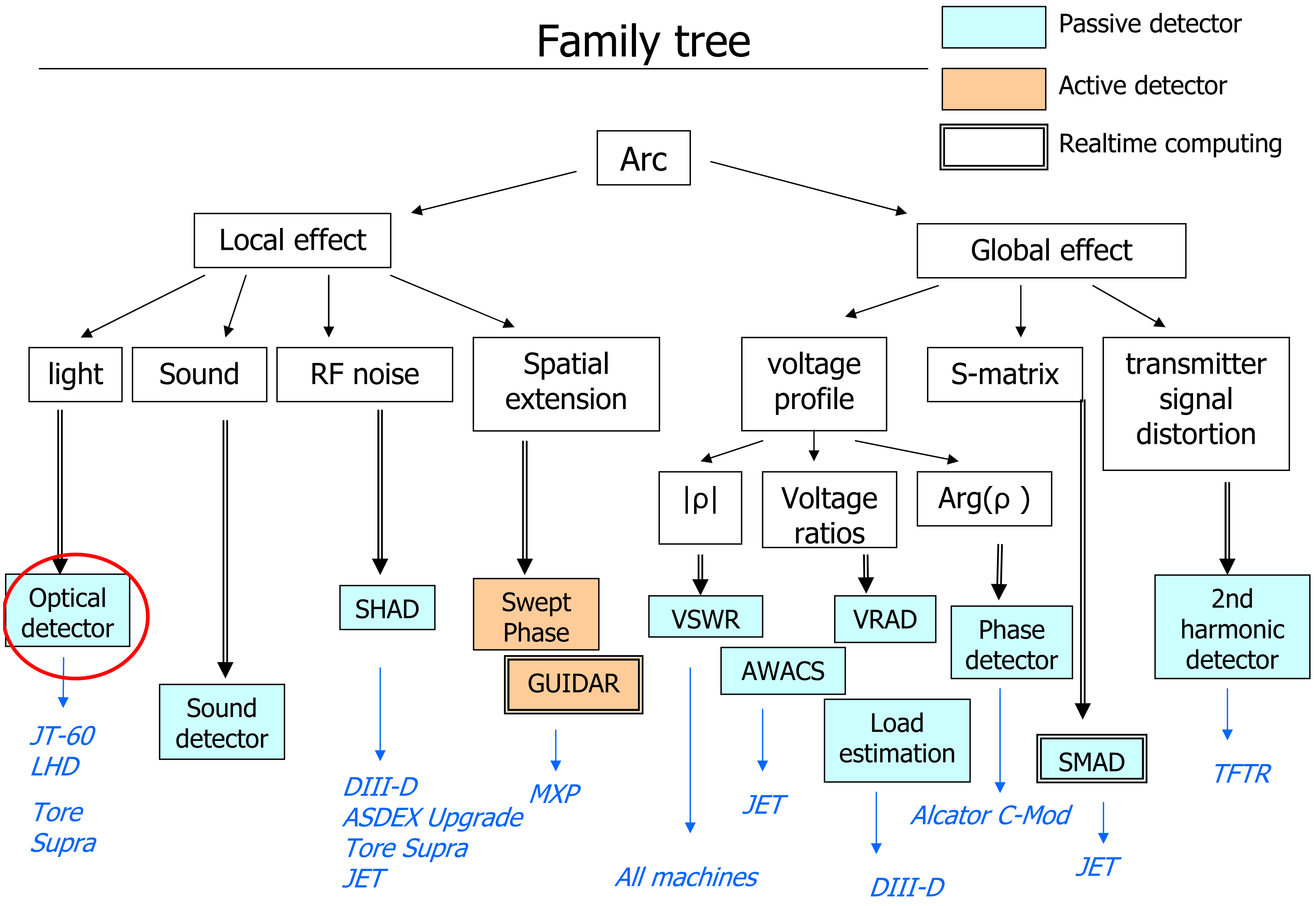
P. Jacquet, Poster B-22 this conference

SHAD: problem of spurious detections

Montage of all signals received in the TL of ASDEX Upgrade
over several discharges (transmitter frequencies are filtered)



Family tree



🟦 Passive detector

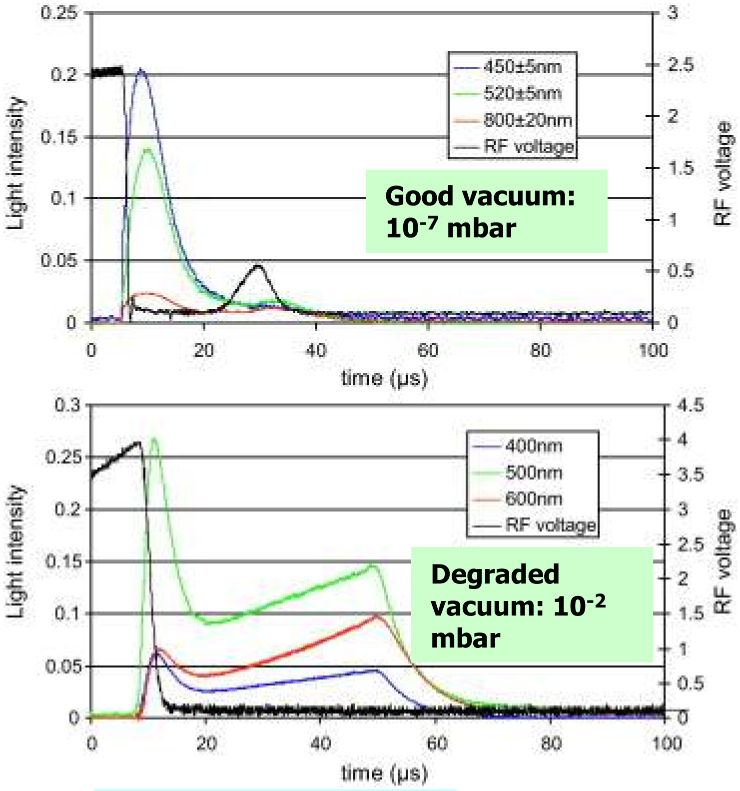
🟧 Active detector

☐ Realtime computing

- Arc
  - Local effect
    - light
      - Optical detector
        - *JT-60*
        - *LHD*
        - *Tore Supra*
    - Sound
      - Sound detector
    - RF noise
      - SHAD
        - *DIII-D*
        - *ASDEX Upgrade*
        - *Tore Supra*
        - *JET*
    - Spatial extension
      - Swept Phase
      - GUIDAR
        - *MXP*
  - Global effect
    - voltage profile
      - |ρ|
        - VSWR
          - *All machines*
      - AWACS
        - *JET*
      - Voltage ratios
        - VRAD
      - Load estimation
        - *DIII-D*
      - Arg(ρ)
        - Phase detector
          - *Alcator C-Mod*
    - S-matrix
      - SMAD
        - *JET*
    - transmitter signal distortion
      - 2nd harmonic detector
        - *TFTR*

Optical detectors

Light emitted by a high voltage arc on the MXP testbed



Good vacuum: 10^{-7} mbar

Degraded vacuum: 10^{-2} mbar

P. Dumortier, SOFT 2010

Light is the simplest way known to detect ghost arcs.

However:

Arcs have to be in the line of sight of the detector: coverage of only single components (vacuum windows, T-Junctions)

They cannot work too near from the plasma because of the optical pollution from the plasma.

They cannot discriminate arcs from strong multipactor: may be a problem for conditioning

Problem of maintenance: dust deposition, irradiation of optical fibers

Intrusive system: complex design, problem of reliability

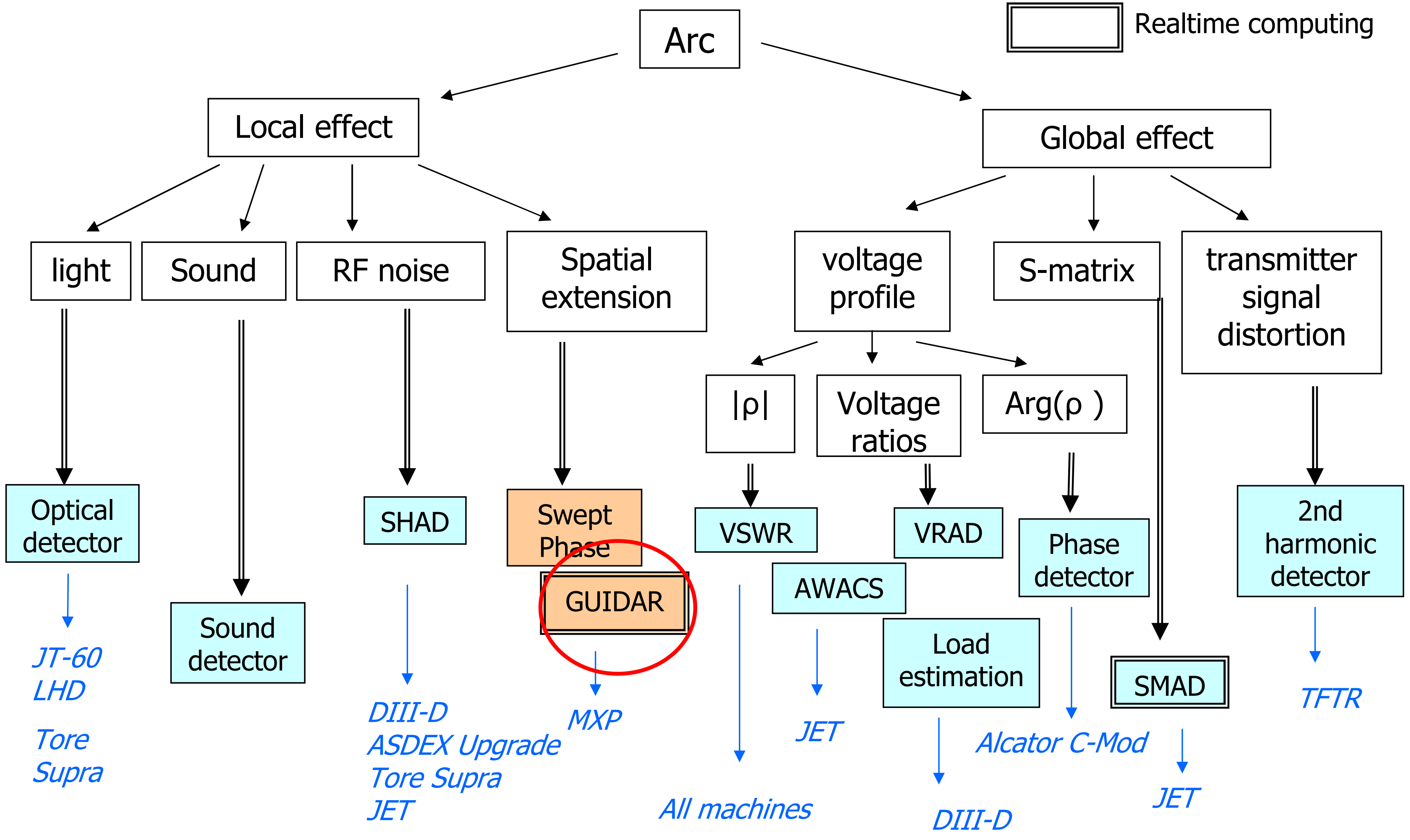
Optical detector for the vacuum feedthrough on LHD

Family tree

🟦 Passive detector

🟧 Active detector

▭ Realtime computing



Arc

Local effect

Global effect

light

Sound

RF noise

Spatial extension

voltage profile

S-matrix

transmitter signal distortion

|ρ|

Voltage ratios

Arg(ρ)

Optical detector

SHAD

Swept Phase

GUIDAR

VSWR

VRAD

Phase detector

2nd harmonic detector

AWACS

Sound detector

Load estimation

SMAD

JT-60
LHD

Tore Supra

DIII-D
ASDEX Upgrade
Tore Supra
JET

MXP

All machines

JET

DIII-D

Alcator C-Mod

JET

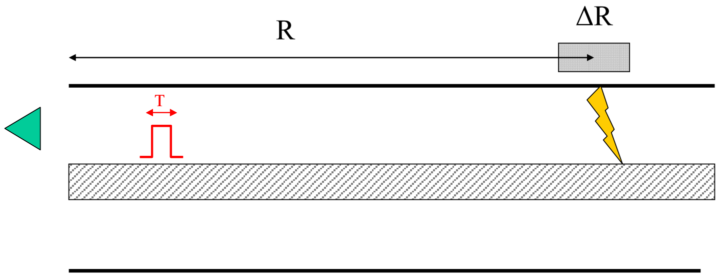
TFTR

GUIDAR

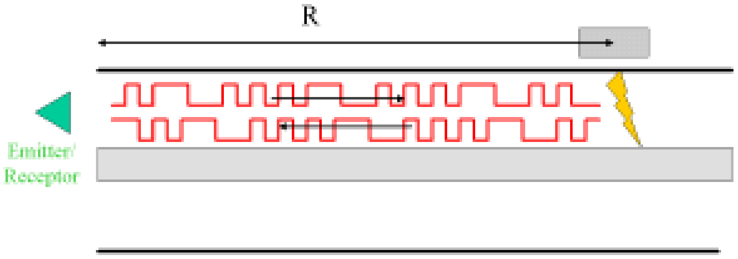
S. Salvador, Poster B-53 this conference

UWB radar: one short pulse, excellent accuracy, sensitive to background noise and jitter.

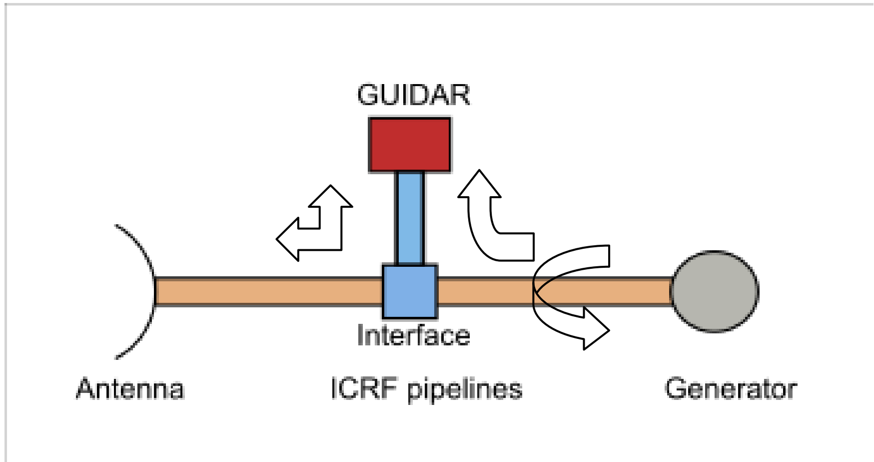
$$\Delta R = \frac{c \cdot T}{2}$$



Pulse compression scheme: train of pulses with phase coding. Increase of signal energy, less sensitive to noise



2 main problems:



- Injection and reception with tractable SNR of GUIDAR signal in transmission line with high level of RF power from transmitters.
2 solutions: septate coupler or directional couplers.

- Interaction of GUIDAR probing wave and ghost arcs, discrimination from plasma instabilities.

Status: very first tests ongoing on the MXP testbed

Summary: detection compliance

S. Huygen, Poster B-21 – This conference

To detect

To discriminate

	VSWR	SHAD	Optical	2^{nd} harmonic	Phase	SMAD	Swept	GUIDAR
HV arc	🟩	🟩	🟩	🟩	🟩		🟩	🟩
Vacuum Feedthough arc	🟥	?	🟩	?	?	🟩	?	?
Antenna arc	🟥	?	🟥	?	?	🟥	?	?
short circuits	🟥	?	🟩	?	🟩	🟩	?	?
Plasma instabilities	🟥	🟩	🟩	?	?	🟩	?	?
Plasma emission	🟩	🟥	🟩	?	🟩	🟩	🟩	?
EMC	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟥
TRL	8	7	3	4	5	4	3	2
Reliability	🟩	🟩	🟥	🟩	🟩	🟥	?	🟥
Cost	+++	++	+	++	+++	-	+	--

Not a single detector meets all requirements

- A lot of unknowns
- Such a matrix is not sufficient to make a decision on the choice of detector(s)

~ Part 4 ~

Towards a detection system for ITER

Requirements and Design

Requirements

Types of arcs to detect	Local properties (light, noise), global properties (effect on VSWR…), energy released
Maximal time delay to detect and switch off the transmitter	Depend on the energetic profile of an arc
Probability to detect an arc	98%,99%,99.9999%? Depends probably on the type of arc and the damage it can cause.
Operation phases	The requirements also depend on the operational phase: during conditioning "controlled" sparking or conditioning should be tolerated => detection only of high energy arcs
Maximum False alarm rate	Direct impact on the efficiency of the ICRF system
Position evaluation and associated accuracy	If arcing is due to a defect, good way to localize it.
EM environment	Impact on the shielding
Nuclear environment	Impact on the position of the probes before or after bio-shield
Realtime diagnosis	Analyze the behavior of the detectors
Maintenance	Choice of material, of position
Reliability	Related to maintenance and to types of detector – Testing before each discharge.

Design

2 strategies for design

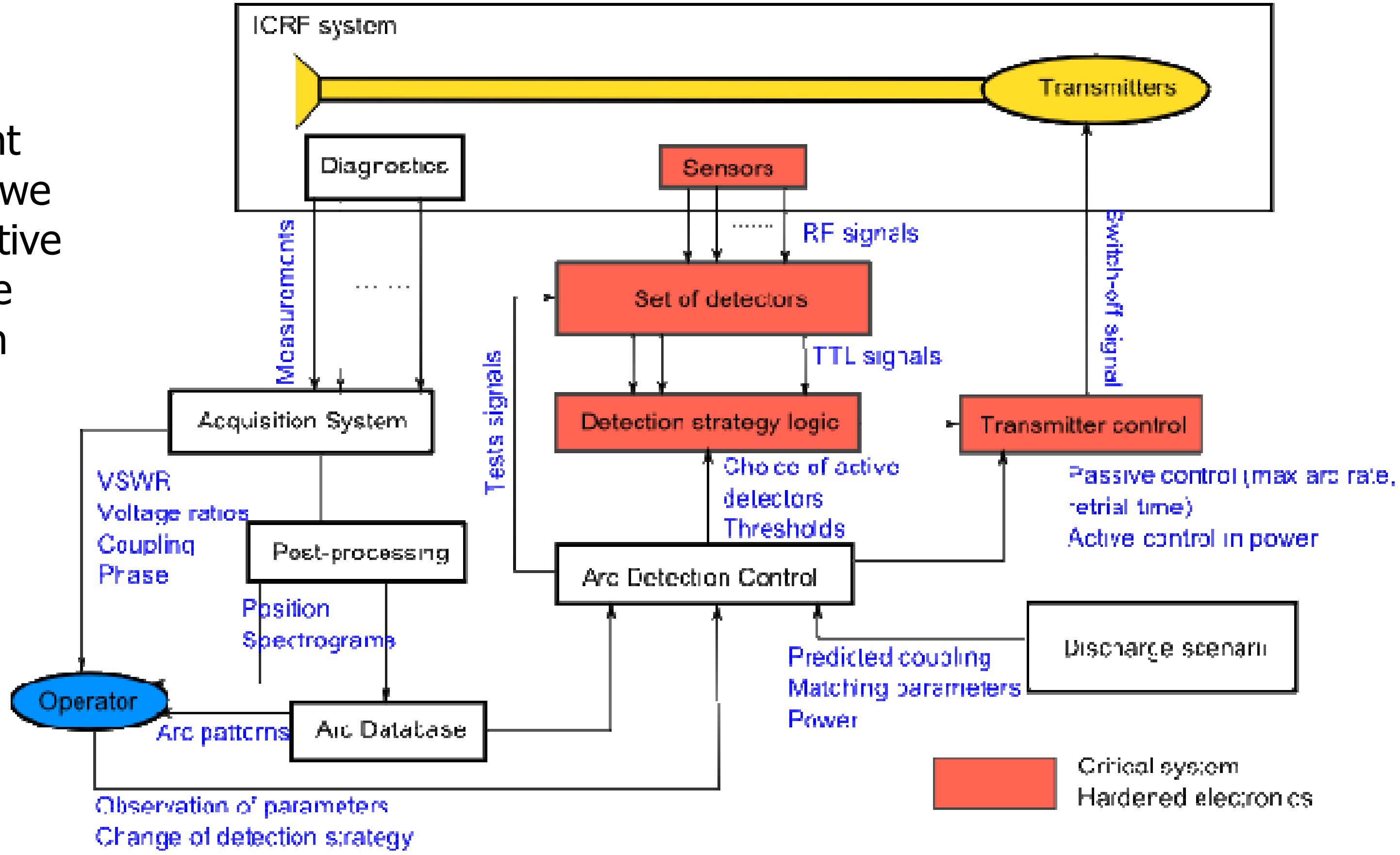
Improve one detector so that it meets all requirements

Best solution, but probably not feasible

Use a set of detectors so that each type of arc is detected at least by one detector

Safest solution but increase of complexity and risk of failure

Taking into account the requirements, we can sketch a tentative architecture for the ITER Arc Detection System



ICRF system
Transmitters
Diagnostics
Sensors
RF signals
Measurements
Set of detectors
TTL signals
Switch-off signal
Tests signals
Acquisition System
Detection strategy logic
Transmitter control
VSWR
Voltage ratios
Coupling
Phase
Post-processing
Choice of active detectors
Thresholds
Passive control (max arc rate, retrial time)
Active control in power
Arc Detection Control
Position
Spectrograms
Discharge scenari
Predicted coupling
Matching parameters
Power
Operator
Arc patterns
Arc Database
Observation of parameters
Change of detection strategy
🟥 Critical system
Hardered electronics

~ Conclusion ~

How to justify the reliability of an arc detector?

Justification

- Arcs are a statistical phenomenon: the justification will be essentially based on statistics

Multi-machine database of arc events and their detection on present ICRF systems

Purpose is to systematically classify arcs with their properties and their probability to be detected

Documentation of all post-campaign inspections

Purpose is to show a trend in the decrease of damages related to arcs

- Middle scale testbeds to test under controlled conditions detectors and to analyze the physics of arcs. Large scale testbeds to investigate arcs on antennas.

- Numerical model to simulate reaction of ICRF system to arcs and plasma instabilities to validate physics at stake and optimize detectors.