22nd International Conference on Gas Discharge and Their Applications

September, 2-7, 2018.

Novi Sad - Serbia

# Reporting AAE

Y. CRESSAULT, Ph ROBIN-JOUAN

12/06/2019

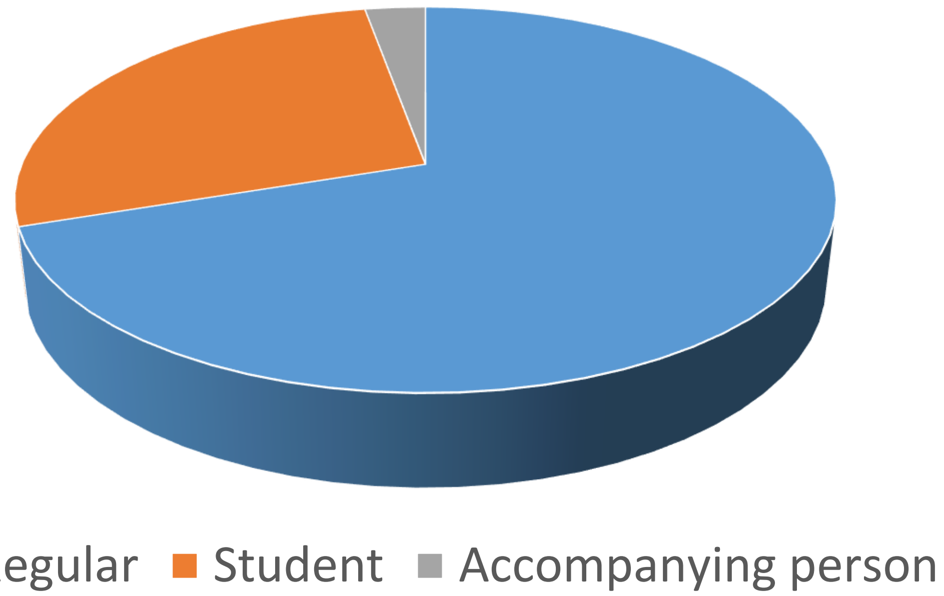
# Location


République
tchèque
Slovaquie
unich
Vienne
Autriche
Hongrie
Slovénie
Croatie
Rou
aint-Marin
Serbie
Sarajevo
Italie
Kosovo
Sofia
Podgorica
Rome
Macédoine
Albanie
Naples
rrhénienne
Thraci
Grèce
Aeg
Mer Ionienne
Athènes
Gulf of Catania
mer de My

# Executive Management Committee

Dr. J.E. Jones, Chair
Prof. G.R. Jones
Prof. J.W. Spencer
Prof. K Hidaka
Dr. A.B. Murphy
Prof. D. Hong
Dr. P. Robin-Jouan

# Attendees



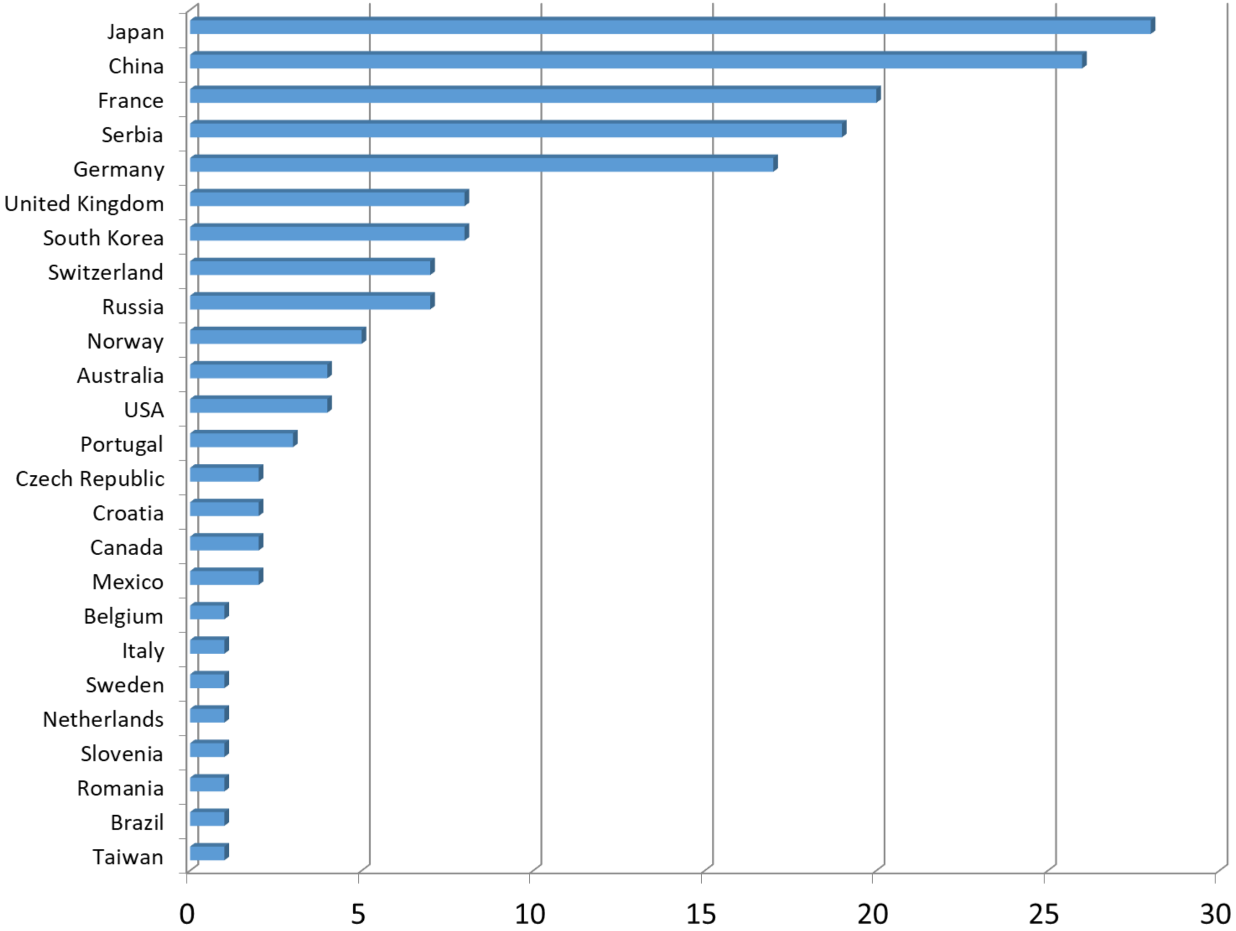

| | |
|---|---|
| Invited lectures | 10 |
| Oral presentations | 125 |
| Workshop progress reports | 15 |

| | |
|---|---|
| Participants<br>Total number | 176 |
| Regular/students | 123/48 |
| Accompanying persons | 5 |

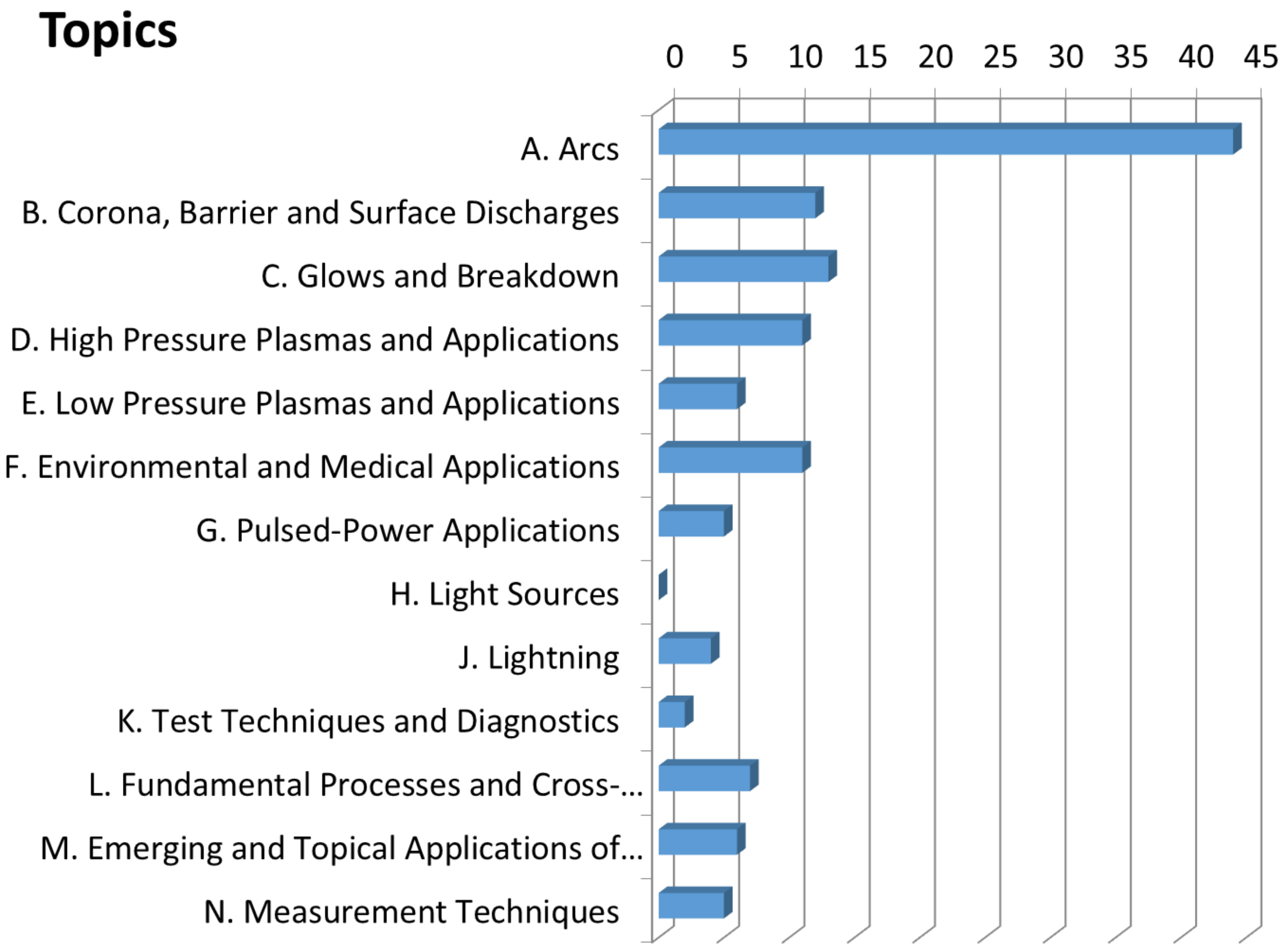
# Attendees

# Attendees


OPEN
TO MORE

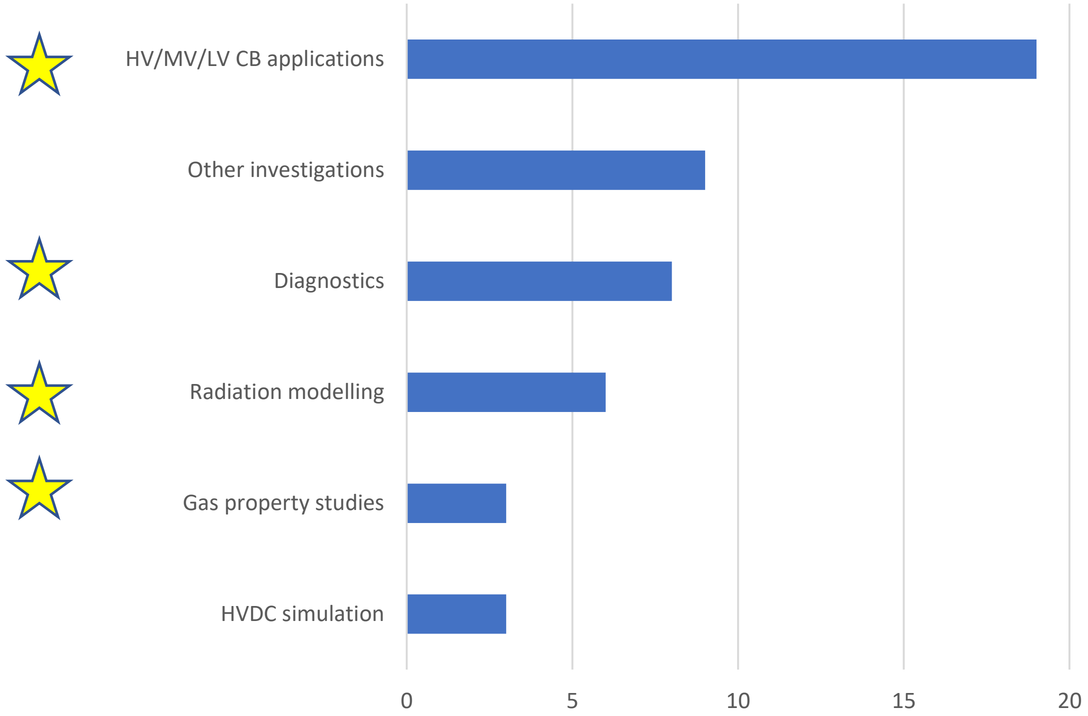

Japan
China
France
Serbia
Germany
United Kingdom
South Korea
Switzerland
Russia
Norway
Australia
USA
Portugal
Czech Republic
Croatia
Canada
Mexico
Belgium
Italy
Sweden
Netherlands
Slovenia
Romania
Brazil
Taiwan
0
5
10
15
20
25
30

# Topics

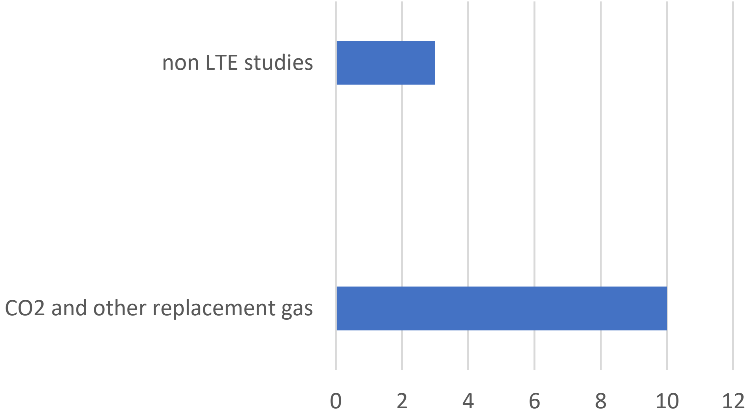



125 papers

# ARC topics Papers




48 papers




# INVITED TALKS

*1/NUMERICAL AND EXPERIMENTAL STUDY OF ARC FAULT IN ARONAUTICAL CONDITIONS*
*2/ELECRIC BREAKDOWN IN HIGH VOLTAGE GAS CIRCUIT BREAKERS*
*3/THE VERIFICATION OF A COMPUTATIONAL MODEL OF ARC MOTION USING AN ARC IMAGING SYSTEM*

# ABLATION STUDIES

*1/CALCULATION MODEL DEVELOPMENT OF PTFE NOZZLE ABLATED MASS AND PRESSURE CHANGES IN HIGH-VOLTAGE CIRCUIT BREAKER*
*2/OPTICAL EMISSION SPECTROSCOPY OF ABLATION-DOMINATED ARCS DURING HIGH-CURRENT PHASE AND AROUND CURRENT ZERO*
*3/INVESTIGATION OF C2 SWAN BANDS IN OPTICAL EMISSION AND ABSORPTION SPECTROSCOPY OF ABLATION-DOMINATED ARCS*
*4/EVAPORATION-DETERMINED MODEL FOR CATHODIC HEATING IN GMA WELDING*
*5/CHARACTERISTICS OF CONTACT EROSION AT ARC INITIATION IN LOW VOLTAGE SWITCHES*
*6/UNIFIED TRANSFER MATRIX EVALUATION OF THE EMISSION CURRENT DENSITY FROM NON-REFRACTORY CATHODES OF ELECTRIC ARCS*
*7/EFFECTS OF ENCLOSURE WALL MATERIAL ABLATION ON ARC VOLTAGE-CURRENT-CHARACTERISTICS*
*8/MODELLING OF NOZZLE ABLATION IN GAS-BLAST CIRCUIT BREAKERS CONSIDERING ITS ACCUMULATIVE EFFECT DUE TO GEOMETRIC VARIATION*
*9/SYSTEMS MODELING OF HIGH-VOLTAGE GAS-INSULATED CIRCUIT BREAKERS*

# + Workshop on Ablation interaction arc-materials

*Mikhail S. Benilov : Recent advances in simulation of plasma-electrode interaction in arc discharges*
*Margarita Baeva : The bidirectional electrodes-plasma interaction as indispensible part of advanced arc plasma*
*Yasunori Tanaka : Spallation occurrence from polyamide materials exposed by thermal plasma*
*Joseph D. Yan : Inclusion of nozzle dimensional change due to PTFE ablation in switching arc simulation*
*Philippe Robin-Jouan : Ablation modelling in High Voltage circuit-breakers: impact on the arc extinction*
*Simon Marek : Evaporation-based model for plasma-cathode attachement in GMA welding*

# PROPERTIES STUDIES

*1/ COMPARISON OF CALCULATED TRANSPORT PROPERTIES WITH MEASUREMENTS IN A WIDE PRESSURE RANGE*

*2/LAST DEVELOPMENT RESULTS FOR 170kV CIRCUIT-BREAKER PROJECT USING g3 GAS*

*3/NUMERICAL STUDY ON CO2 GAS CIRCUIT BREAKER USING SEMI-EMPIRICAL MODEL FOR RADIATIVE ENERGY TRANSFER*

*4/RADIATIVE TRANSFER CALCULATION OF CO2 THERMAL PLASMA USING A HYBRID PLANCK-ROSSELAND MEAN ABSORPTION COEFFICIENT*

*5/DIELECTRIC PROPERTIES OF HOT C5F10O AND ITS MIXTURES WITH CO2 AT THE ELEVATED TEMPERATURE*

*6/CHEMICALLY NON-EQUILIBRIUM STATE IN SF6 ARC PLASMAS DUE TO THE VARIATION AND SPATIAL GRADIENT IN TEMPERATURE*

*7/PRESSURE DEPENDENCE OF THE OPTIMIZED MEAN ABSORPTION COEFFICIENTS*

*8/SYSTEMATIC INVESTIGATION ON RADIATION MODELING ERRORS OF A WALL-STABILIZED ARC SIMULATIONS*

*9/COMPARISON OF DIFFERENT MODELS TO CALCULATE THE COMPOSITION AND THERMODYNAMIC PROPERTIES OF A MULTI-TEMPERATURE SF6 PLASMA*

# INVITED TALKS

*1/NUMERICAL AND EXPERIMENTAL STUDY OF ARC FAULT IN ARONAUTICAL CONDITIONS*

*2/ELECRIC BREAKDOWN IN HIGH VOLTAGE GAS CIRCUIT BREAKERS*

*3/THE VERIFICATION OF A COMPUTATIONAL MODEL OF ARC MOTION USING AN ARC IMAGING SYSTEM*

**NUMERICAL AND EXPERIMENTAL STUDY OF ARC FAUL IN AERONAUTICAL CONDITIONS**

*J.M. BAUCHIRE, M.LISNYAK, H.RABAT, M.CHNANI, A.BIGAND, C.ESPINOSA*

**Etude :** arc de défaut dans le domaine de l'aéronautique :
étude expérimentale et modélisation du déplacement d'un arc entre deux bus-barres (partie 1),
Dommage d'un arc électrique sur matériaux composites (partie 2)

**Objectif principal :** prédire par le modèle le déplacement de l'arc entre bus-barre, interaction arc-matériau

## Etude expérimentale du déplacement d'un arc entre deux bus-barres

Mesures $I_{arc}$ (t), $V_{arc}$ (t), vitesse pied d'arc (cathode, anode)
Caméra rapide
Distance inter-électrode : 5 ou 8mm
Electrode en Al
Amorçage par fil contact
420-760Hz
I=400A-2kA
115V ou 230$V_{RMS}$

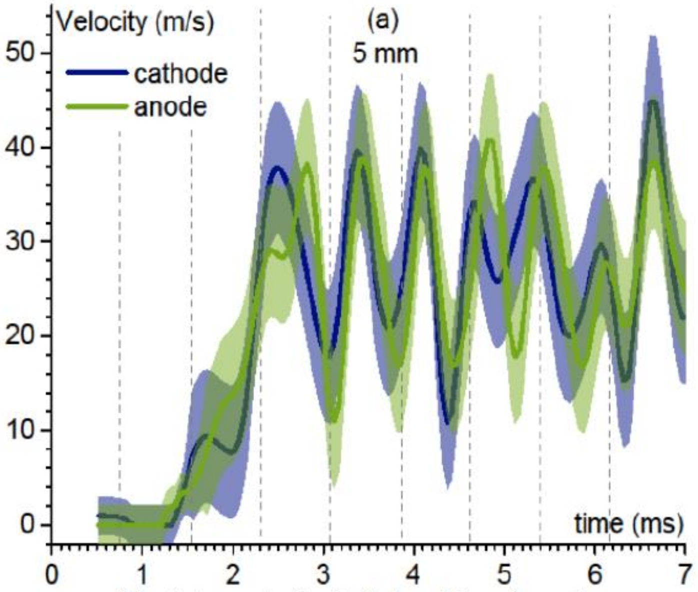



*Fig. 4 Arc root velocity deduced from figure 1*

Vitesse pied : max 40m/s
Durée déplacement : 6-7ms

*J.M. BAUCHIRE, M.LISNYAK, H.RABAT, M.CHNANI, A.BIGAND, C.ESPINOSA*

## Etude numérique du déplacement d'un arc entre deux bus-barres : MHD COMSOL

Etude de $V_{arc}$(t), $I_{arc}$(t) : bon accord sur la forme avec légère sous-estimation de $V_{arc}$(t) car non prise en compte chute tension Aux électrodes

Vitesse v(t) au centre de l'arc et attachement anodique bien reproduit

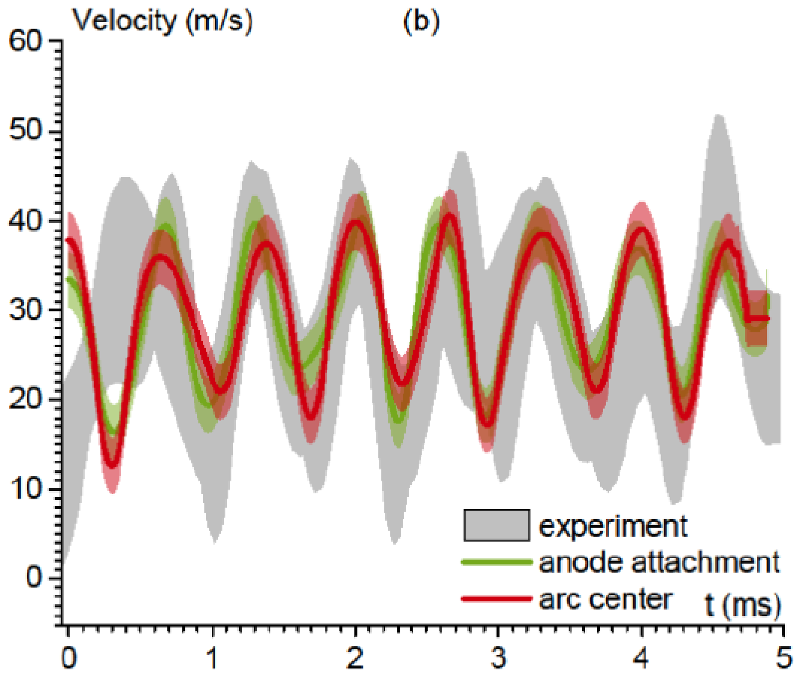


*Fig. 6 Arc root velocity (7690 Hz, 5 mm)*

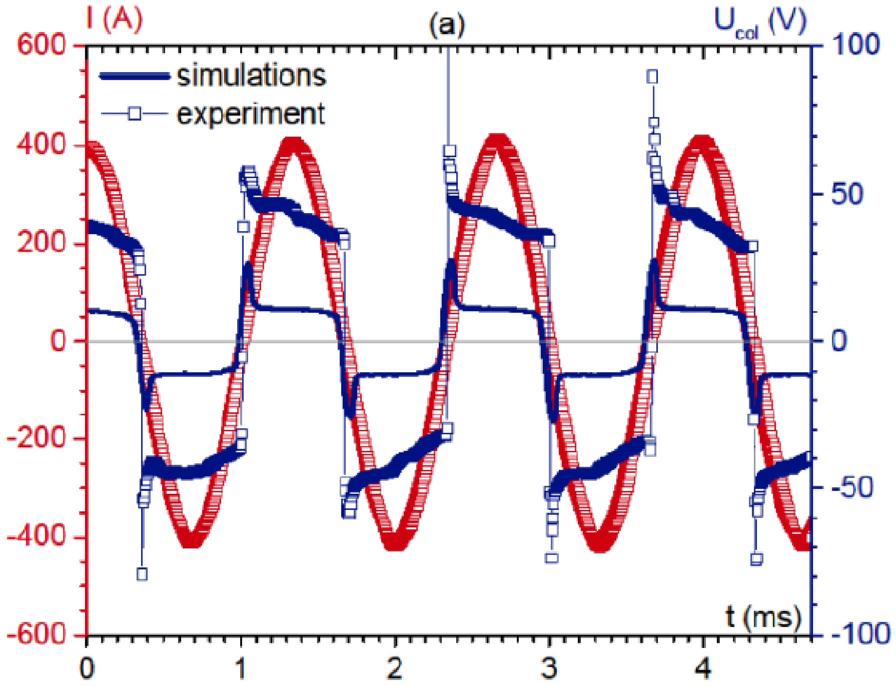
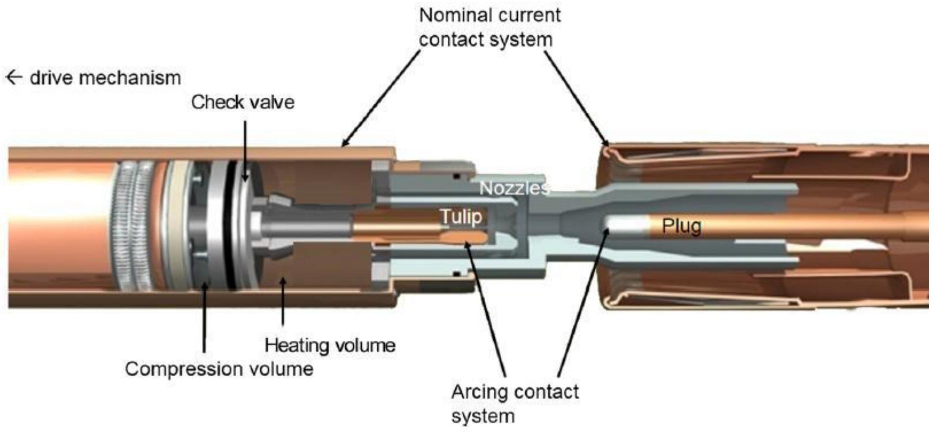


*Fig. 5 Arc current and voltage waveforms (750 Hz, 5mm)*

ELECTRICAL BREAKDWON IN HIGH VOLTAGE GAS CIRCUIT BREAKERS

*M.SEEGER*

**Etude :** étude d'un arc dans un HVCB du claquage à l'extinction (CZ) et après (**reclaquage**)



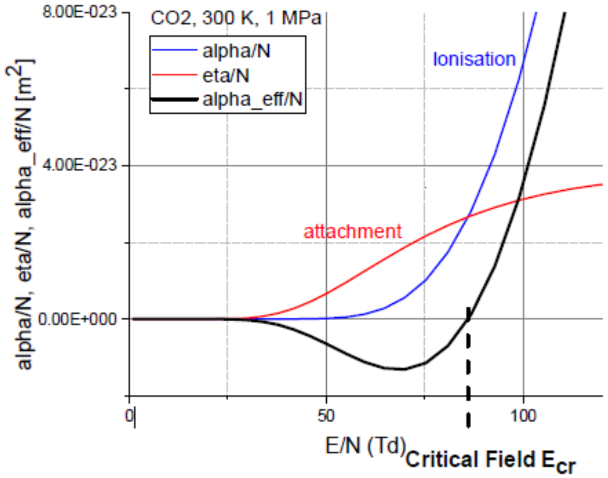




*Fig. 2 Ionisation, attachment and effective ionisation coefficient in $CO_2$, at 1 MPa*

***Rappels sur les propriétés diélectriques des gaz et leur impact sur la coupure***

$(E/N)_{crit\_SF6}$=89*Pression

$(E/N)_{crit\_CO2}$=23*Pression

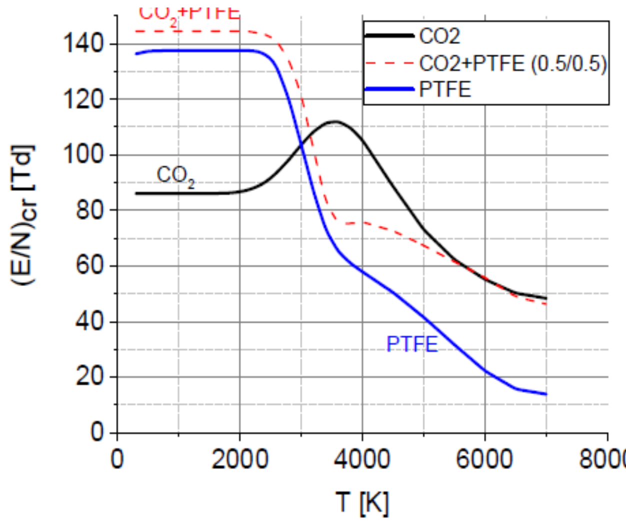



*Fig. 3 Particle density reduced critical electric field in CO2 and $C_2F_4$ (PTFE) mixtures at 1 MPa*

## Claquage à température ambiante

- Importance du 1er électron (statistical time lag STL) : ***Plus E est grand, plus petit est STL (polarité négative***
- Importance du streamer (création) : ***Stabilité du streamer***
- Importance des mécanismes de chauffage streamer-to-spark, streamer-to-leader transition : ***dépendent de la tension appliquée, et du temps, important dans l'air. Succession de mécanismes***

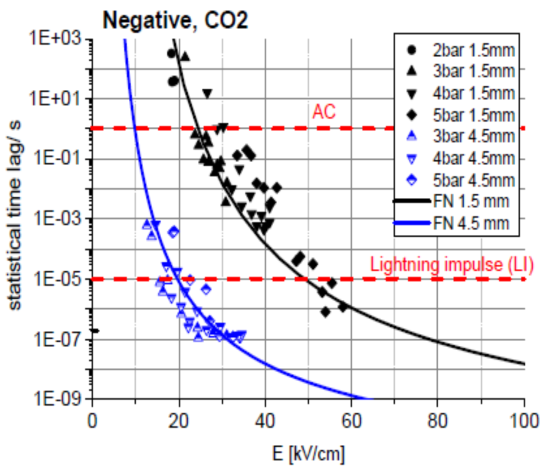
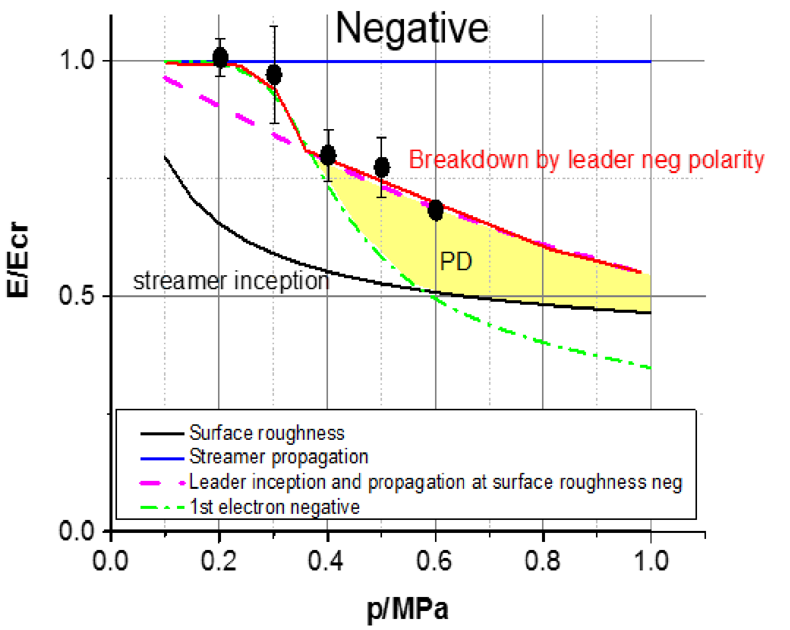
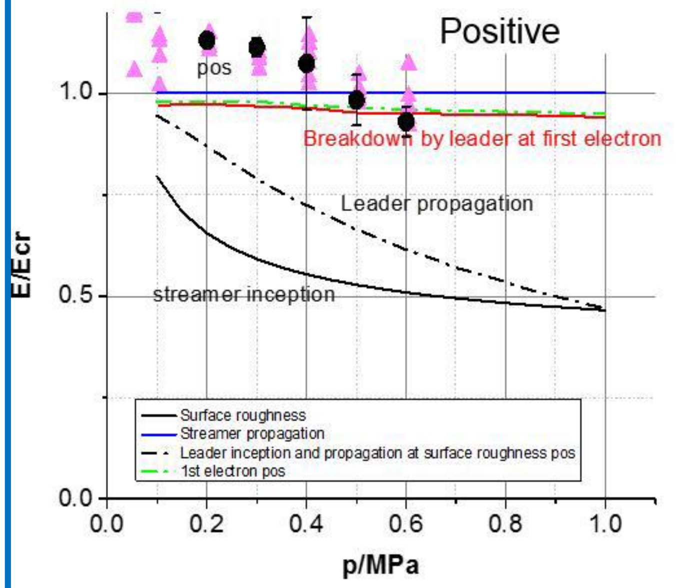



*Fig. 4 Statistical time lags vs electric field strength in $CO_2$ at a small protrusion in the range of 1.5...4.5 mm lengths at various pressures from 0.2...0.5 MPa. The lines results from a fit, using field electron emission [4].*



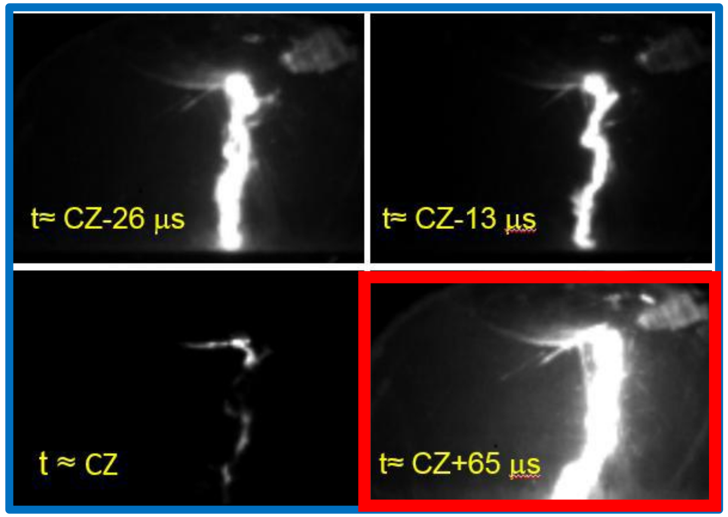




*Reduced breakdown fields at rough HVCB plug in SF6 vs pressure for positive and negative polarity. The breakdown field is normalised to the critical field. The symbols are experimental results in a plug-plate arrangement. Various criteria are shown by the curves. These were achieved by assuming a 100mm protrusion at the surface. PD denotes the region with possible partial discharges.*

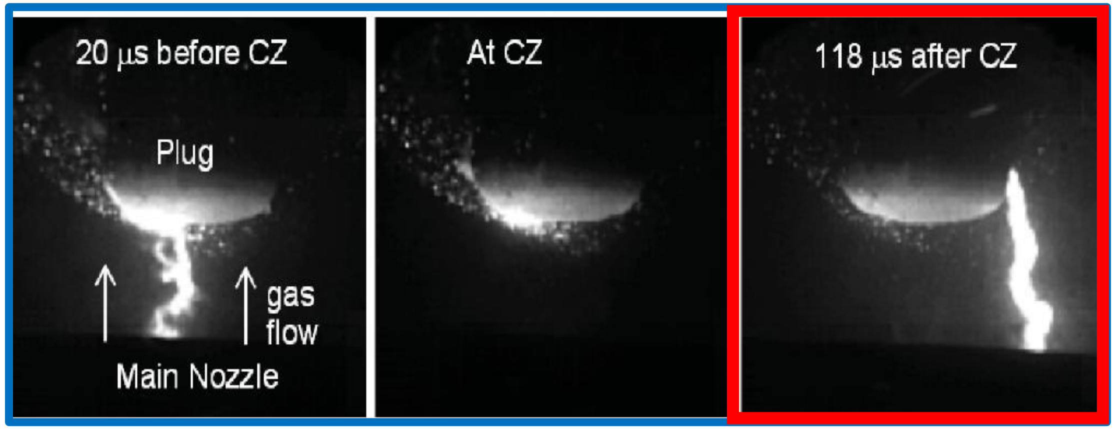
## Claquage à haute température après CZ

- Au CZ, toujours un canal d'arc (5000K, 10000K…)
- Rupture de type « thermique », en raison du canal d'arc, courant post arc (PAC), augmentation de la tension de récupération transitoire (TRV) peu de temps après CZ. Les temps de rupture dépendent du gaz et sont dans la gamme de quelques 100 nanosecondes (p. ex., SF6) à quelques secondes microsecondes (p. ex., CO2).

- Importance du $\rho.C_p$, turbulence, pression, coefficient d'attachement électronique, effets déséquilibre (thermiques, chimiques)




*Breakdown at a HVCB plug in SF6. The arc before CZ and the breakdown after CZ is shown. The current peak was about 5 kA and the breakdown voltage about 190 kV. The direction of the gas flow is indicated by the arrows.*




*Breakdown at a HVCB plug in $SF_6$. The arc before CZ and the breakdown after CZ is shown. The current peak was about 23 kA and the breakdown voltage about 240kV. The direction of the gas flow is indicated by the arrows.*

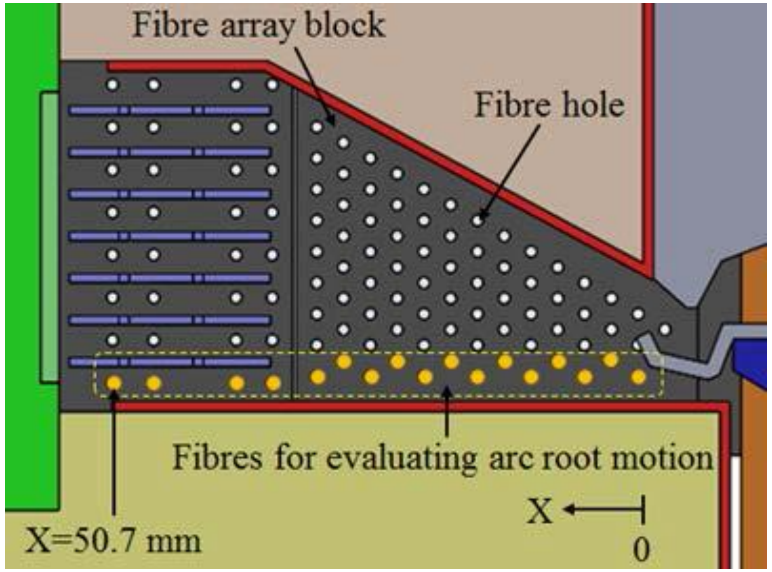
# THE VERIFICATION OF A COMPUTATIONAL MODEL OF ARC MOTION USING AN ARC IMAGING SYSTEM

*J.W. MCBRIDE*

**Etude :** déplacement d'un arc dans un LVCB (modélisation et étude expérimentale par caméra), dans les splitters

**Historique :** utilisation fibre optique 1992-2003, étude sur disjoncteur commercial 1994 (influence of circuit magnétique sur mouvement de l'arc) , influence de l'ouverture des contacts sur pieds d'arc, mouvement pieds anodiques et cathodique durant ouverture contact, étude commutation de l'arc, érosion des contacts, vitesse pieds d'arc sur contacts piezo, diagnostic par imagerie fibre optique (1998-2010)

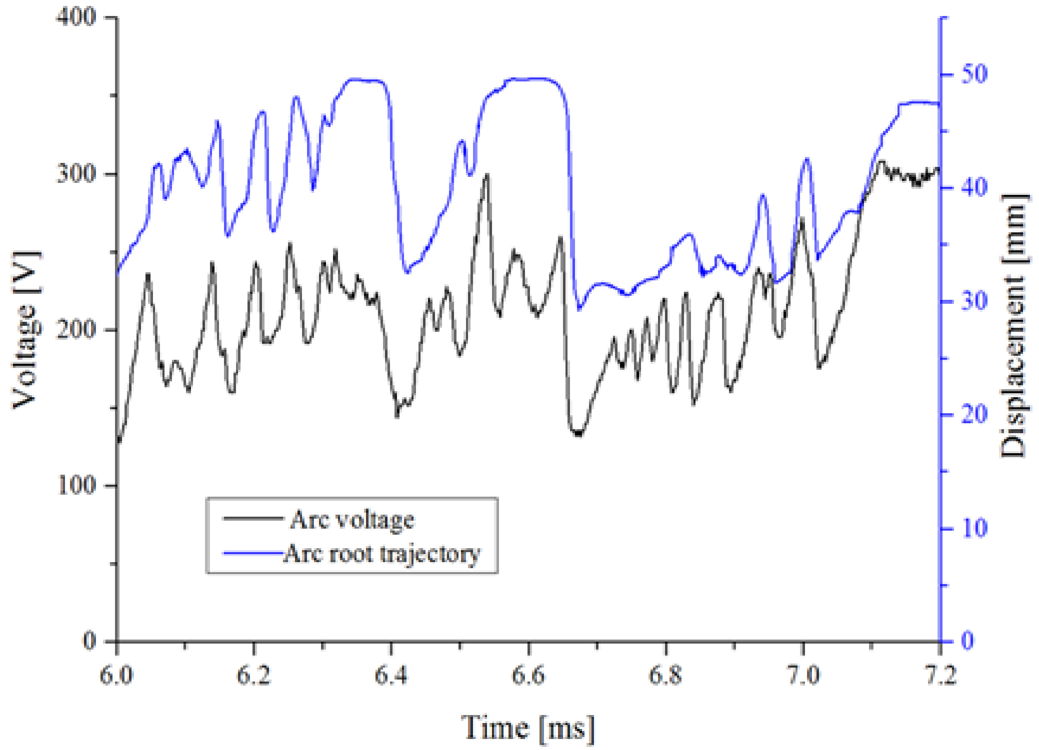
| | Max Value | Experiment Values |
|---|---|---|
| Sample Rate | 6 MHz | 1 MHz |
| Number of Optical Fibres | 1024 | 120 |
| Number of Frames | 512,000 | 512,000 |
| Capture time | 0.09 sec | 0.5 sec |
| Light Intensity Resolution | 8 bit (0-255) | 8 bit (0-255) |
| Signal Gain | 1-32 | 1-4 |
| Length of Optical Fibre | 100 m | 2 m |
| Light Intensity Filter | ND0-16 | ND8 |




*New FTA showing the optical fibre positions, used for evaluation of arc root motion and the position of optical fibres in the splitter plate region. 120 fibres optiques (points blancs), points jaunes pour pieds d'arc (0-50.7mm)*

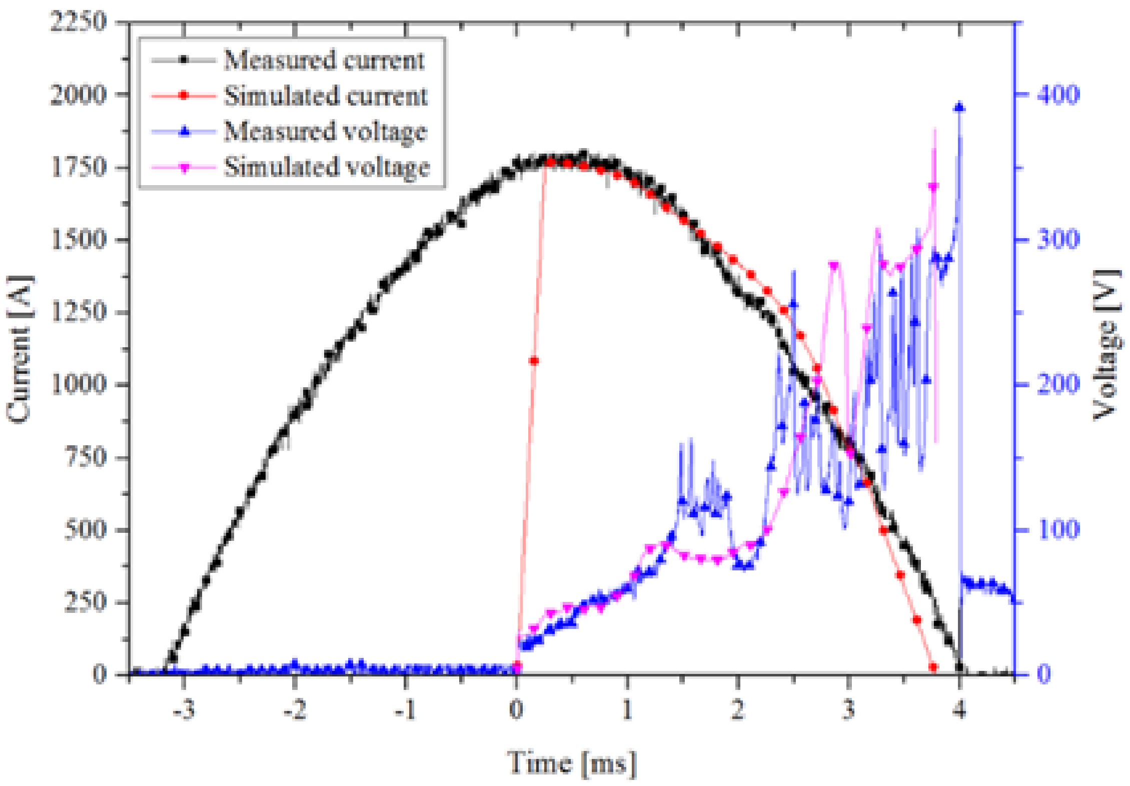
# THE VERIFICATION OF A COMPUTATIONAL MODEL OF ARC MOTION USING AN ARC IMAGING SYSTEM

*J.W. MCBRIDE*




*The arc root trajectory as the arc enters the splitter plates, (X) displacement and arc voltage, for a 200 V, short circuit event.*

***Fluctuation de la tension quand l'arc entre dans les splitters. A 50mm : plasma d'arc montre une instabilité visible sur les fluctuations de tension.***




*Measured and Simulated V,I*

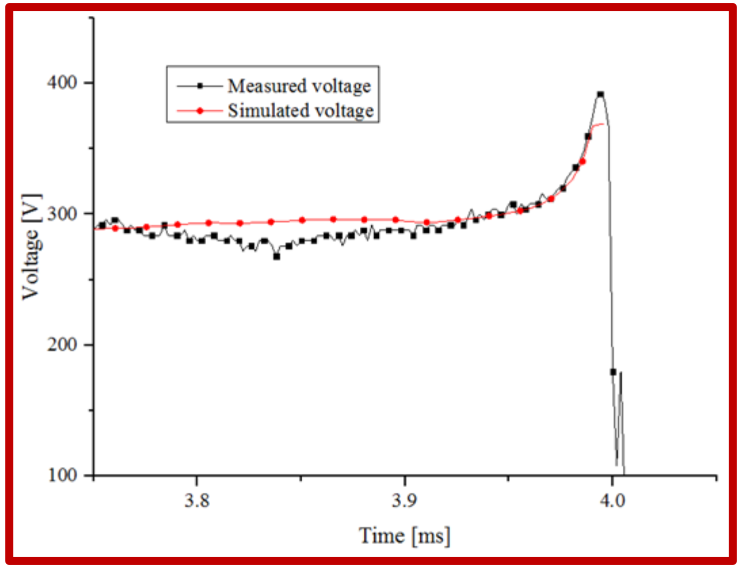
***pour 200V supply, 1750A peak.***

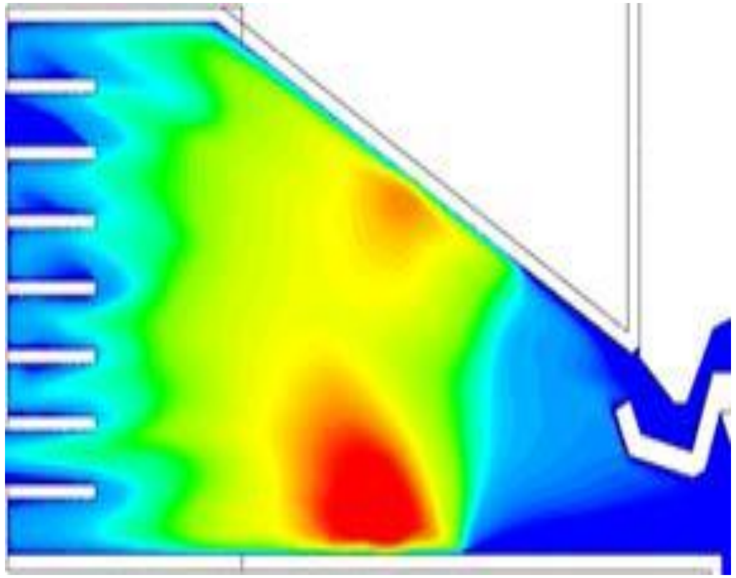
# THE VERIFICATION OF A COMPUTATIONAL MODEL OF ARC MOTION USING AN ARC IMAGING SYSTEM

*J.W. MCBRIDE*

***Images caméra*** : déplacement sur 1.5ms, rentre dans les splitters, restrike à 2ms et re-rentre dans les splitters à 2.3ms. V=150V jusqu'à 80V durant restrike. Après les 2.3ms, fluctuation de $V_{arc}$ et stabilisation à 3.7ms. Tension sortie : 390V

***Modèle:*** même comportement, chute de la tension à 1.7ms, rentrée dans les splitters à 3ms, mouvement retour arrière visible, stabilisation à 3.3ms. Tension sortie plus faible



*200V supply, ND8 filter, Left, plasma temperature at 2ms, (blue below 5,000 K, and red above 19,000 K). Right, the corresponding arc image at frame 5210.*

**Conclusion :** la modélisation caractérise bien le déplacement de l'arc (pieds d'arc), montre bien le lien avec $V_{arc}$, mais n'arrive pas décrire suffisamment bien ce déplacement dans les splitters

# ABLATION STUDIES

1/*CALCULATION MODEL DEVELOPMENT OF PTFE NOZZLE ABLATED MASS AND PRESSURE CHANGES IN HIGH-VOLTAGE CIRCUIT BREAKER*

2/*OPTICAL EMISSION SPECTROSCOPY OF ABLATION-DOMINATED ARCS DURING HIGH-CURRENT PHASE AND AROUND CURRENT ZERO*

3/*INVESTIGATION OF C2 SWAN BANDS IN OPTICAL EMISSION AND ABSORPTION SPECTROSCOPY OF ABLATION-DOMINATED ARCS*

4/*EVAPORATION-DETERMINED MODEL FOR CATHODIC HEATING IN GMA WELDING*

5/*CHARACTERISTICS OF CONTACT EROSION AT ARC INITIATION IN LOW VOLTAGE SWITCHES*

6/*UNIFIED TRANSFER MATRIX EVALUATION OF THE EMISSION CURRENT DENSITY FROM NON-REFRACTORY CATHODES OF ELECTRIC ARCS*

7/*EFFECTS OF ENCLOSURE WALL MATERIAL ABLATION ON ARC VOLTAGE-CURRENT-CHARACTERISTICS*

8/*MODELLING OF NOZZLE ABLATION IN GAS-BLAST CIRCUIT BREAKERS CONSIDERING ITS ACCUMULATIVE EFFECT DUE TO GEOMETRIC VARIATION*

9/*SYSTEMS MODELING OF HIGH-VOLTAGE GAS-INSULATED CIRCUIT BREAKERS*

# CALCULATION MODEL DEVELOPMENT OF PTFE NOZZLE ABLATED MASS AND PRESSURE CHANGES IN HIGH-VOLTAGE CIRCUIT BREAKER

*M. SATO, K. HORINOUCHI, S. HIZA, Y. NAKAMURA, Y. YOSHITOMO, Y. SHIMIZU, and Y. YOKOMIZU*

**Etude :** ablation PTFE – $SF_6$, variation de la pression dans un HVCB -> influence sur la capacité de coupure
**Objectif :** prédire la masse ablatée de la tuyère, calcul de la variation de la pression, comparaison avec mesures
**Postulat :** masse ablatée proportionnelle à l'énergie rayonnée (absorbée par PTFE)

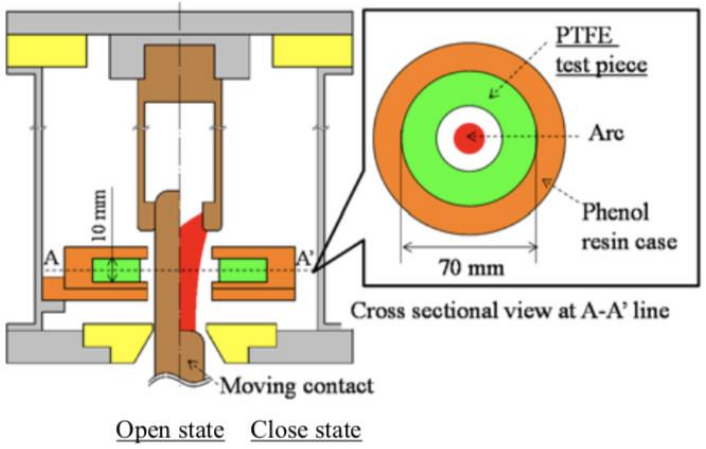



*Fig. 1 Cross-sectional view of arc apparatus to investigate PTFE ablated mass characteristics.*

$$m = a_3 \cdot \left[\frac{R_w \cdot K_1\left(R_w\sqrt{3k_p k_r}\right)}{r_a \cdot K_1\left(r_a\sqrt{3k_p k_r}\right)}\right] \cdot i^{1.2}$$

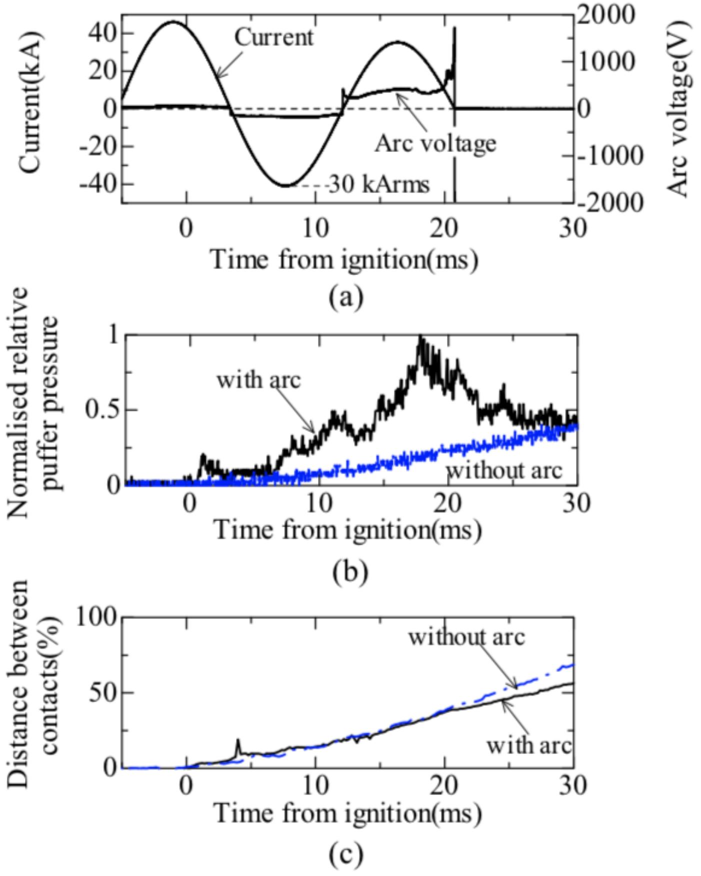



*Fig. 5 Example waveforms for current, arc voltage, pressure in a pressure chamber and distance between contacts.*

**<u>Données :</u>** Planck-Mean $K_p$ et Rosseland-Mean $K_r$ pour le coefficients d'absorption
Pression mesurée par un capteur piézoélectrique
$a_3$ est issu de l'expérience = $2.39 \times 10^{-2}$
$r_a$ rayon de l'arc $SF_6$, $R_W$ rayon de la pièce testée

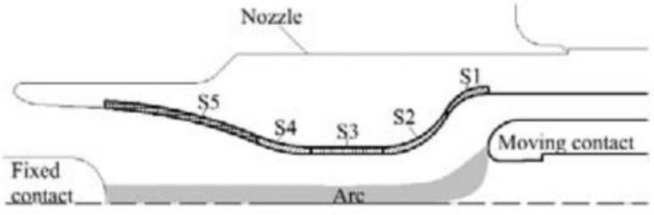
# CALCULATION MODEL DEVELOPMENT OF PTFE NOZZLE ABLATED MASS AND PRESSURE CHANGES IN HIGH-VOLTAGE CIRCUIT BREAKER

*M. SATO, K. HORINOUCHI, S. HIZA, Y. NAKAMURA, Y. YOSHITOMO, Y. SHIMIZU, and Y. YOKOMIZU*

## Mesures obtenues :

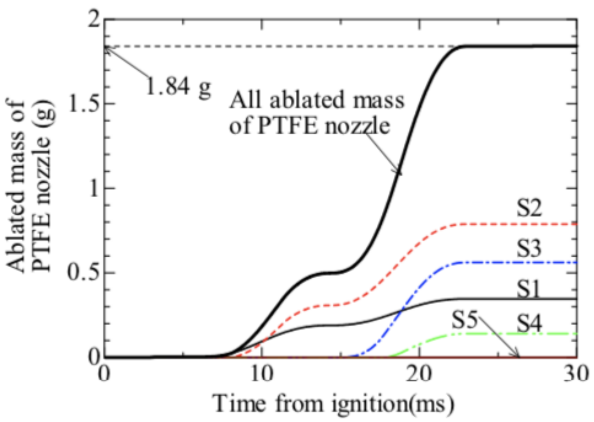
**P=** 0.5 Mpa

$T_{arc}$-->21ms, P-->$P_{max}$ à 18ms, 5 essais




(b)

*Fig. 6 Calculated result of nozzle ablated mass.*




(a)

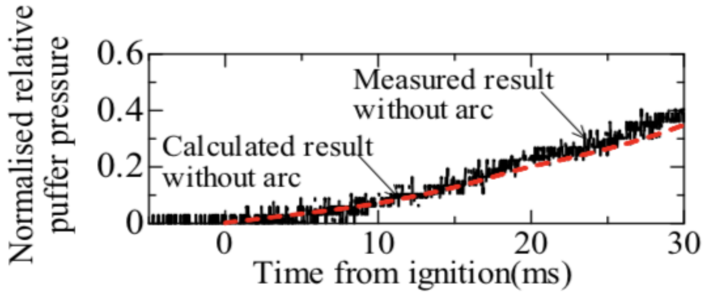
$M_{perdue}$ après 5 tests = 11,7g
$Mc_{alculée}$ par la fomule = 9,9g

## Model ablation:

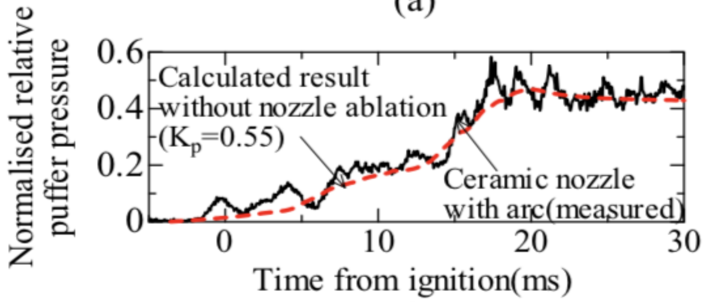
Appareillage découpé en 7 zones

Equations énergie+masse ablatée – 1D steady-state

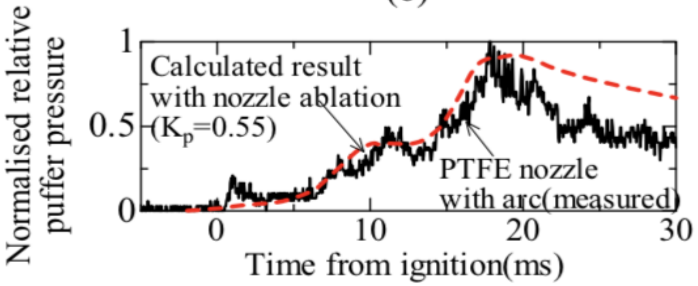
Sans arc + céramique $ZrSiO_4$ (pas d'ablation) + PTFE




(a)




(b)




(c)

**OPTICAL EMISSION SPECTROSCOPY OF ABLATION-DOMINATED ARCS DURING HIGH-CURRENT PHASE AND AROUND CURRENT ZERO**

K.-D. WELTMANN, R. METHLING, N. GÖTTE, S. WETZELER, AND D. UHRLANDT

### *Conditions expérimentales*

- Ablation 2ms avant l'extinction (dernières ms avant le CZ)
- Intensité de l'ordre de kA, $CO_2$, électrodes en CuW + nozzle PTFE
- 50Hz, 5kA peak, 40mm électrodes gap, 4mm nozzle distances
- Disjoncteur réel -> expérience sur chambre simplifiée -> analyse expérimentale

### *Outils et méthodes*

- OES en phase de fort courant + en phase Zero Current

- Camera rapide à travers fenêtre de visée + ICCD : résolution FWHM=0.3nm, $\Delta\lambda=150$nm, 50$\mu$m fente, 1image/1$\mu$s

- Mesures du rayonnement des raies $C^{n+}$, $F^{n+}$, $O^{n+}$ + paramètres électriques + pression totale

- Détermination de T(r,t) - axisymétrique + optiquement mince, inversion d'Abel, coefficient d'émission

- Spectromètre 0.5m de focale, 150 traits/mm

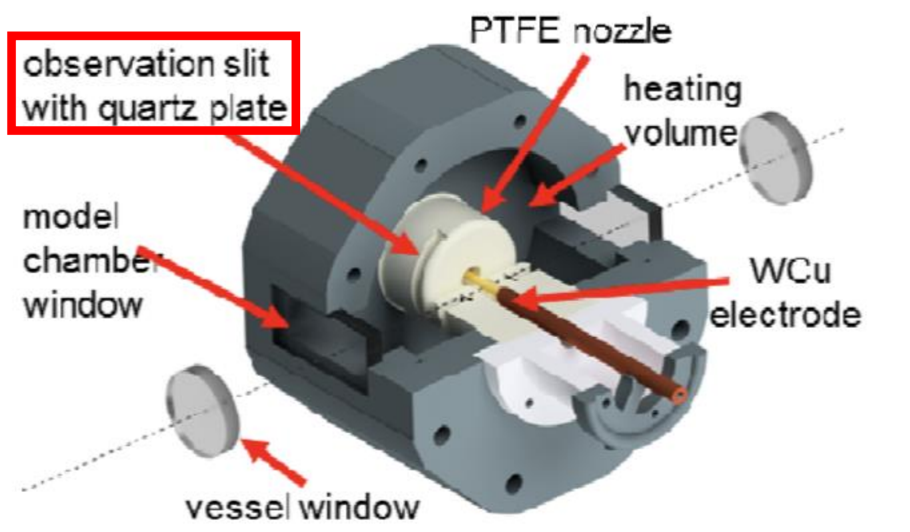



*Fig. 1 Model circuit breaker geometry. The arc is ignited by wire (thickness 50 µm) explosion and operated between to electrodes surrounded by nozzles. Observation is realized via slits in the nozzles that are covered by quartz plates, and windows in the model chamber and the outer high-pressure vessel (not shown here).*

**OPTICAL EMISSION SPECTROSCOPY OF ABLATION-DOMINATED ARCS DURING HIGH-CURRENT PHASE AND AROUND CURRENT ZERO**

K.-D. WELTMANN, R. METHLING, N. GÖTTE, S. WETZELER, AND D. UHRLANDT1

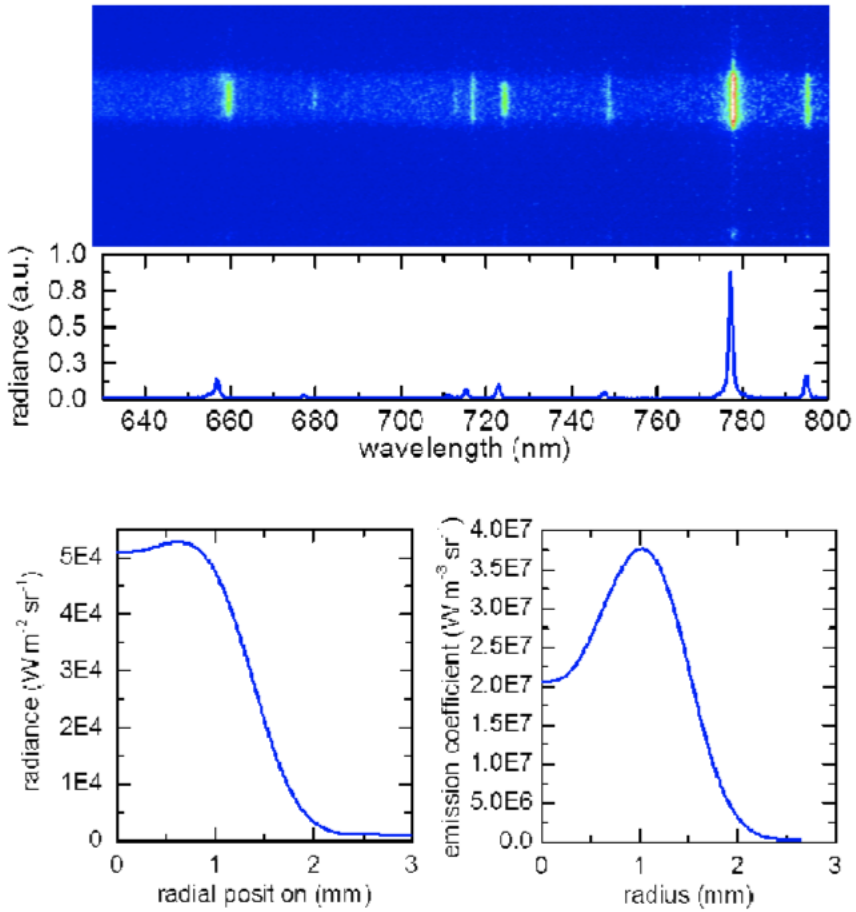



*Fig. 2 Two-dimensional spectrum measured 300 μs before CZ (top). Vertical axis comprises the nozzle diameter. Side-on radiance integrated over the O I 777 nm triplet (bottom left) and deduced emission coefficient (bottom right) show a distinct maximum caused by the higher ionisation degree in the arc centre.*

$P_{max}$ à 1mm, T-16000K, P-1.2 bar

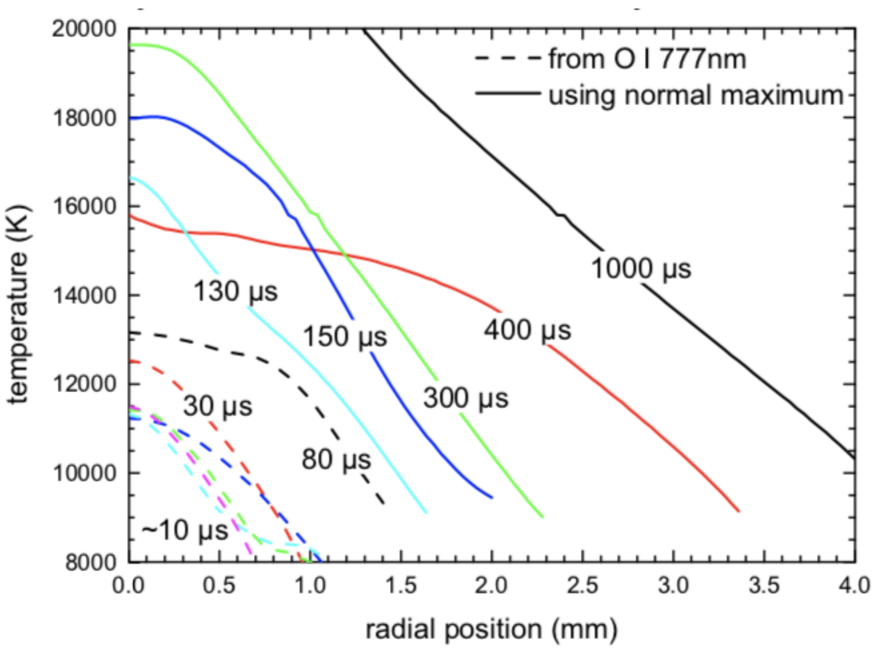



*Fig. 4 Plasma temperatures at different instants of time before CZ.*

à 1ms avant CZ : raies F visibles (disparaissent ensuite)
à 300µs avant CZ : T=20000K,raies O et $C^+$ visibles, I=500A
à 100µs avant CZ : T=14000K
à 10µS avant CZ : T=11000K

P=3bar à 0.3 bar

**Futur :** analyse des bandes $C_2$ Swan

# INVESTIGATION OF C2 SWAN BANDS IN OPTICAL EMISSION AND ABSORPTION SPECTROSCOPY OF ABLATION-DOMINATED ARCS

R. METHLING, N. GÖTTE, S. WETZELER, AND D. UHRLANDT, K.-D. WELTMANN

**Etude :** mesure du rayonnement de la bande de C2 Swan pour estimer l'absorption (érosion du carbone)

**Expérience :**

Arc stabilisé, peak de courant à 5kA, électrodes en CuW, gaz $CO_2$ + PTFE
Plasma cylindrique –> Mesure émission –> optiquement mince –> inversion d'Abel –> Température vibrationnelle
Faible I –> faible rayonnement –> gaz froid proche CZ –> températures basses –> OES moléculaire

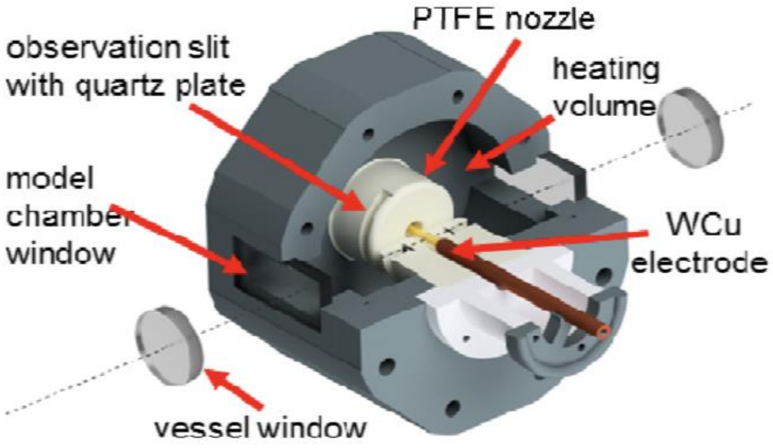



*Fig. 1 Model circuit breaker geometry. The arc is operated between two electrodes surrounded by nozzles. Observation is realized via slits in the nozzles that are covered by quartz plates, and windows in the model chamber and the outer high-pressure vessel.*

Techniques :

OES : analyse du rayonnement du continuum moléculaire du $C_2$ Swan pour avoir la température

Spectroscopie d'absorption, mais difficile sur les raies dans l'UV ou à faible energie

Caméra rapide (Y4 series of Integrated Design Tools, 10 bits monochrom), 10000 fps (1/100$\mu$s), temps exposition 98 $\mu$s

Spectromètre : Roper Acton SpectraPro SP2500i (0.5 focale, 50$\mu$m, 1800 traits/mm, $\Delta\lambda_{enregistrée}=10$nm, FWHM=0.1nm résolution spectrale)

# INVESTIGATION OF C2 SWAN BANDS IN OPTICAL EMISSION AND ABSORPTION SPECTROSCOPY OF ABLATION-DOMINATED ARCS

R. METHLING, N. GÖTTE, S. WETZELER, AND D. UHRLANDT, K.-D. WELTMANN

**Mesures :**

1.5ms après l'extinction, mesure du courant de 2.5kA
Analyse des raies de Cu (500-520nm) pour érosion des électrodes
Analyse des raies de F (624 et 634.8nm) issues de ablation tuyère
Analyse des raies de $C^+$ (564, 566, 589, 610.3nm) issues de $CO_2$
Bandes $C_2$ Swan visibles en émission et absorption

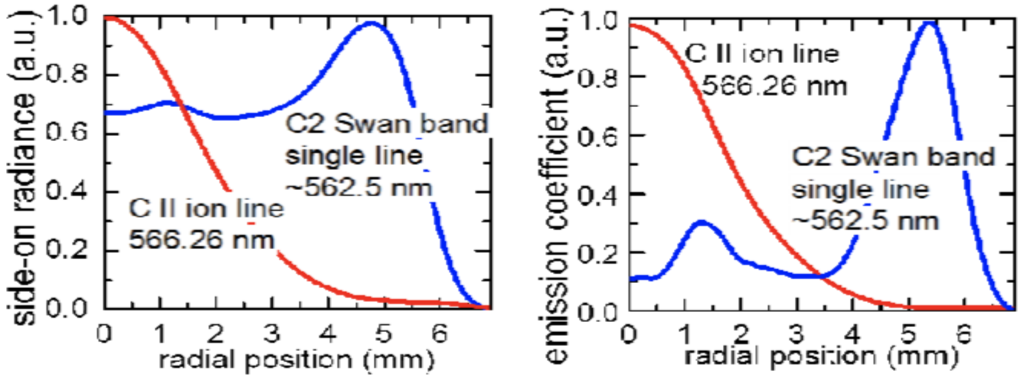



*Fig. 5 Comparison of maxima in the emitted Swan band of Fig. 4a with the local minima in the absorption spectrum of Fig. 4b (top). Relative side-on radiances and deduced emission coefficients of a single C2 band maximum and of a C II ionic line visualizing the different origin of the emission along the arc radius (bottom).*

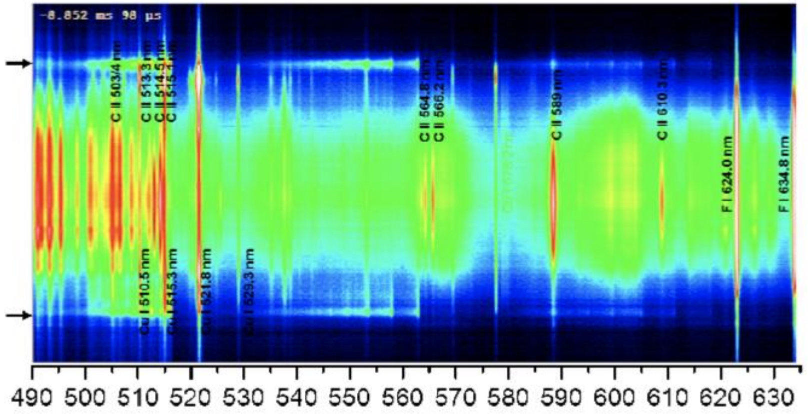



*Fig. 2 Two-dimensional spectrum measured 1.5 ms after ignition. Vertical axis comprises the nozzle diameter.*

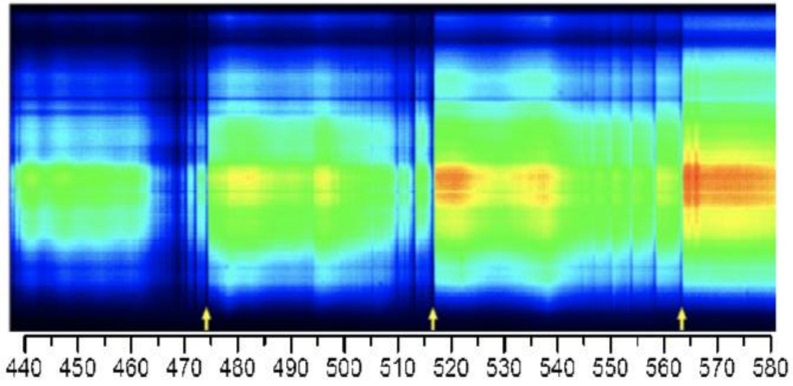



*Fig. 3 Swan bands visible as absorption pattern due to arc emission that serves as backlight. Band heads are indicated by arrows.*

*Détermination $T_{vibrationnelle}$ par comparaison entre mesures et continuum (Bremsstrahlung). Développements encore nécessaires*

# EVAPORATION-DETERMINED MODEL FOR CATHODIC HEATING IN GMA WELDING

O. MOKROV, M. SIMON, A. SCHIEBAHN AND U. REISGEN

**Etude :** ablation de la cathode dans un procédé GMA

**Objectif :** déterminer une relation qui relie heat flux, densité de courant à la $T_{surface}$ de la cathode basé sur un modèle semi-empirique du spot de la cathode + prise en compte des effets d'évaporation

**Hypothèses :**

- Ionisation non linéaire des atomes dans la zone cathodique
- $\Delta v_{cathode}$, épaisseur de la gaine comme entrée du modèle

**Calculs:**

- Flux ionique supposé non linéaire, fonction du courant d'émission thermo-ionique
- Flux d'évaporation
- Prise en compte du bombardement ionique $q_{ion}$, électrons rétro-diffusés $q_{ebd}$, emission thermo-ionique $q_{em}$, évaporation $q_{evap}$, conduction, rayonnement

$T_h = T_{wall}$, $T_e = \frac{(e \cdot U_D + k_B \cdot T_W - e \cdot E_{ion})}{3/2 \cdot k_B}$

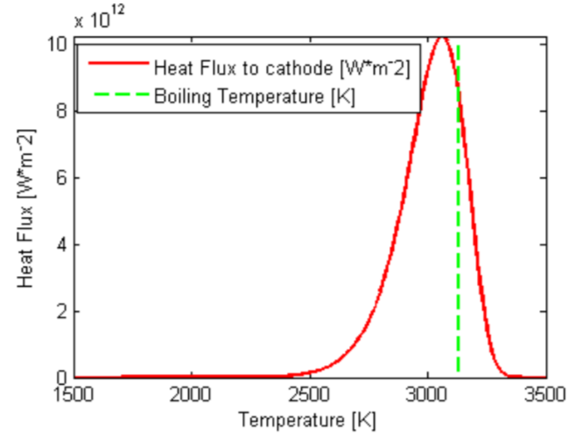
Valeurs/expressions données pour $d_{sheath}$, $U_D$, $W_{sortie}$, $E_{ion}$, $j_{em}$, $j_{ion}$, $P_{vap}$, $q_{ion}$, $q_{ebd}$, $q_{em}$, $q_{evap}$, $j_{vap}$, $q_{rad}$, $q_{totalcathode}$, $P = 5.10^9$ Pa

$$n_{is} = \frac{j_{ion}}{e\sqrt{k_B(T_h + ZT_e)/m_i}}$$

$$p(T) = \frac{n_{is}}{k_B T_h}$$

**Conclusion :** $j_{CS,max} \cdot U_D / q_{CS,max} = 0.76$

CS : cathode spot



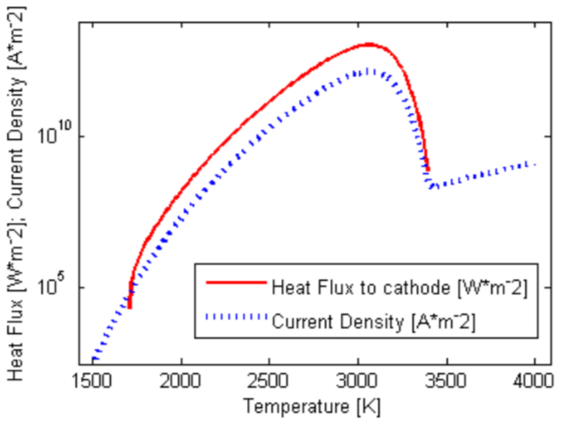




*Fig. 2 Fluxes in Cathode Spot*

# CHARACTERISTICS OF CONTACT EROSION AT ARC INITIATION IN LOW VOLTAGE SWITCHES

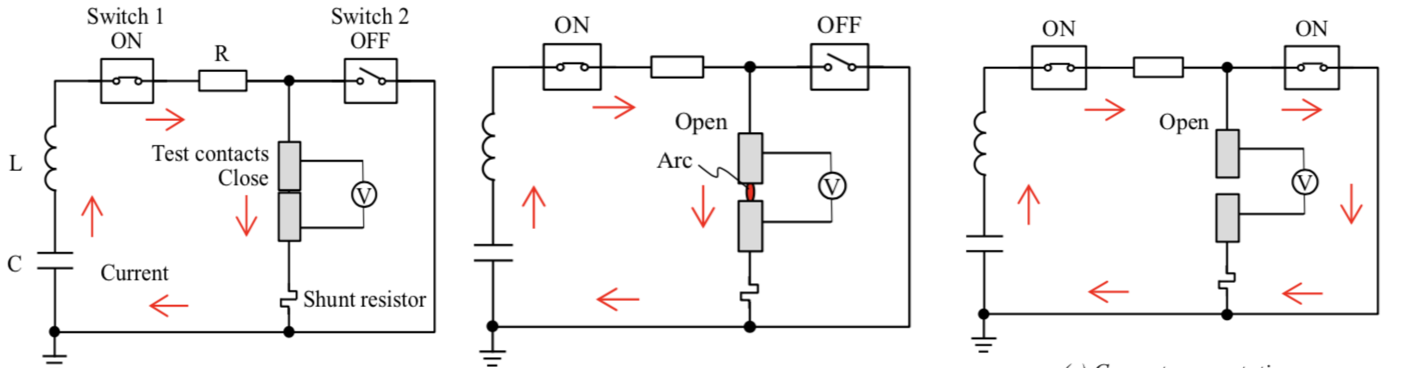
K. HOTTA, S. WATANABE AND T. INAGUCHI

**Etude :** érosion à l'amorçage de l'arc dans un LVCB avec électrodes en Ag

**Constat :** influence de la nature du contact sur la valeur du courant et la durée de l'arc (phénomènes bien connus pour I<100A mais peu pour I>100A)

**Postulat :** Connaître l'érosion c'est connaître la durée de vie de l'arc dans un LVCB

La masse ablatée juste après le « break » est proportionnelle au courant carré du I au début du break




(a) Energization start (b) Arc initiation (c) Current commutation

**Dispositif expérimental**

Circuit électrique avec sonde de courant et sonde de tension

Contacts ϕ=6mm, L=3mm, 99.99%Ag, contacts gap = 3.5mm

$T_{arc}$=1.6 à 24.4ms

Masse des contacts mesurée à 0.01mg

1 contact utilisé pour 10-50 essais

Test pour un courant d'arc de 90A, 170A, 270A, 430A

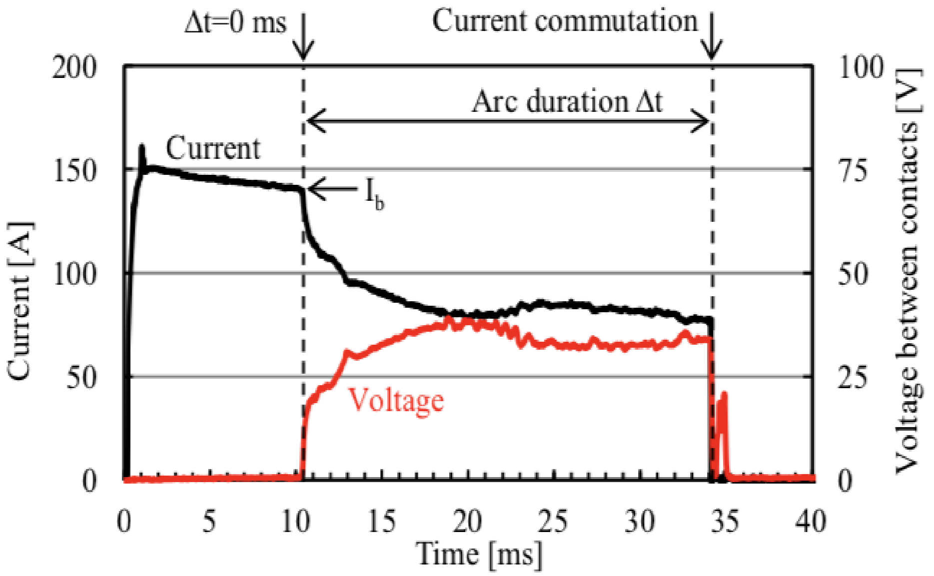



*Fig. 3 Current and Voltage Waveforms*

# CHARACTERISTICS OF CONTACT EROSION AT ARC INITIATION IN LOW VOLTAGE SWITCHES

K. HOTTA, S. WATANABE AND T. INAGUCHI

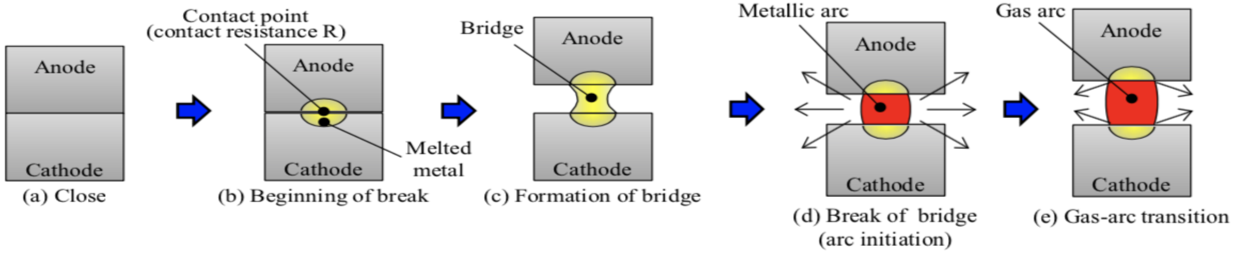
## Résultats

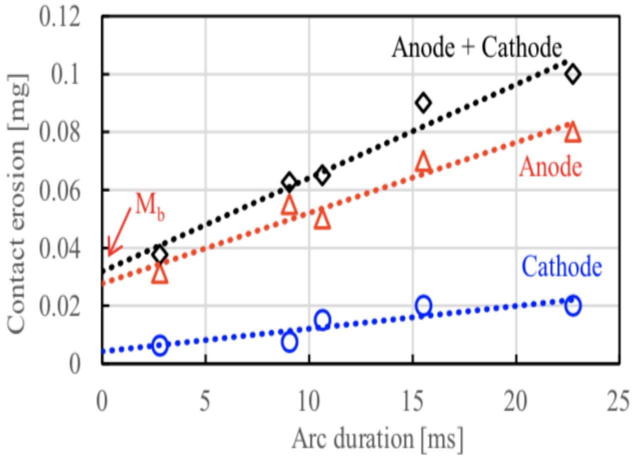
Electrodes en contacts -> break -> bridge -> zone de fusion -> arc métallique -> break bridge

M à la cathode est plus faible qu'à l'anode

M(mg) de contacts érodée varie linéairement avec la durée de l'arc

La masse ablatée est quasi-proportionnelle à $I^2$ -> $M_b = k.I_{break}^{2.1}$




(b) $I_{arc}$ = 170 A

Quand l'intensité augmente, l'érosion augmente
Variation linéaire de l'érosion en fonction du temps d'arc

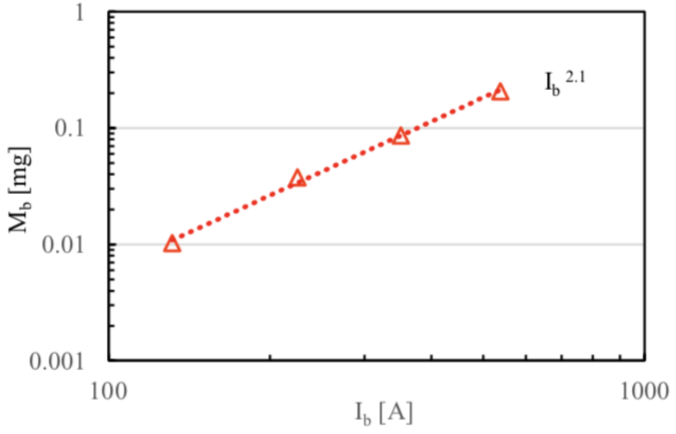



*Fig. 6 Dependence of Contact Erosion at Initiation of Contact Break on Final Contact Current*

$$M_b = k.I_{break}^{2.1}$$

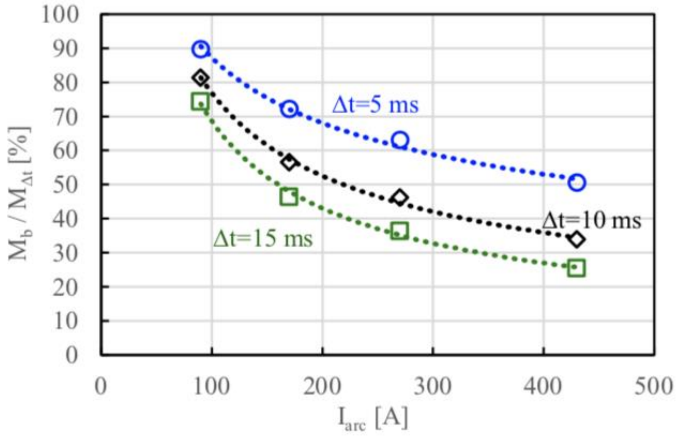
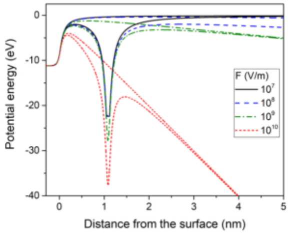



*Fig. 7 Rate of Contact Erosion at Initiation of Contact Break*

1/ $M_b$ grand au début du break
2/ plus Δt est grand, plus le pied d'arc est large, plus $M_{\Delta t}$ est grand (total contact erosion)
3/ The foot diameter of the gas arc becomes large, and the gas arc tends to move on the contact in large current condition

# UNIFIED TRANSFER MATRIX EVALUATION OF THE EMISSION CURRENT DENSITY FROM NON-REFRACTORY CATHODES OF ELECTRIC ARCS

M. BAEVA




***Quand E augmente la barrière diminue***

**Etude :** détermination emission current density d'une surface métallique sans approximation

**Constats :** les formules approchées de Fowler-Nordheim, JWKB, Murphy et Good ne sont pas toujours valables, calcul de l'émission électronique par intégration Numerov de l'équation 1D stationnaire steady-state Schrödinger délicate

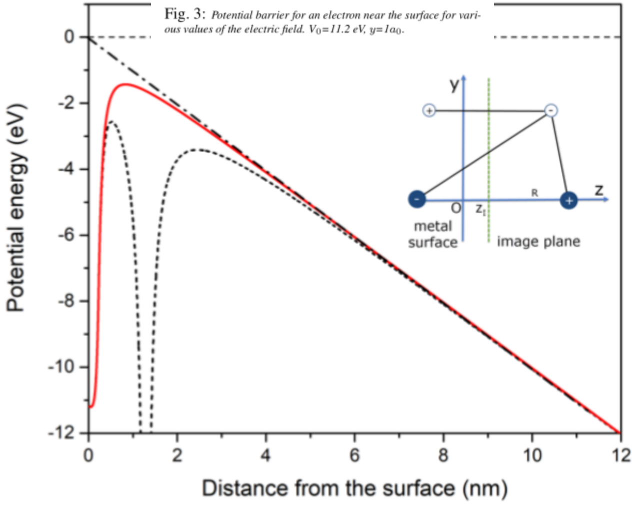



Fig. 3: *Potential barrier for an electron near the surface for various values of the electric field. $V_0$=11.2 eV, $y$=1$a_0$.*

**Objectif :** montrer que la méthode TMM (Transfer Matric Method) fonctionne sans approximations

**Théorie :**

- Cathode non réfractaire, Fermi-Dirac distribution pour les électrons libres dans le métal
- $W_{cathode}$=4.5eV, définition d'une barrière de potentiel
- Expression donnée pour : densité de courant des électrons $j_{em}$ d'une surface métallique à $T_C$

$$J_{em} = e \int_{-\infty}^{\infty} \int_{W_a}^{E} T(F,W)\, \mathcal{N}(T_c,\phi,E)\, dW\, dE$$

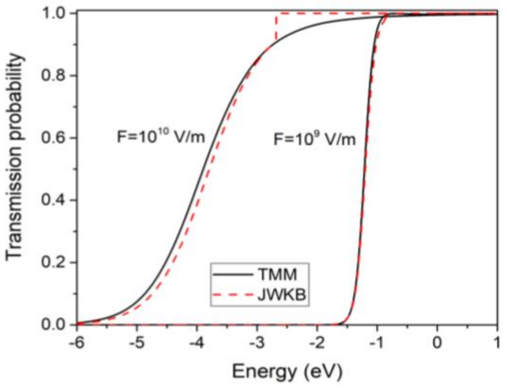
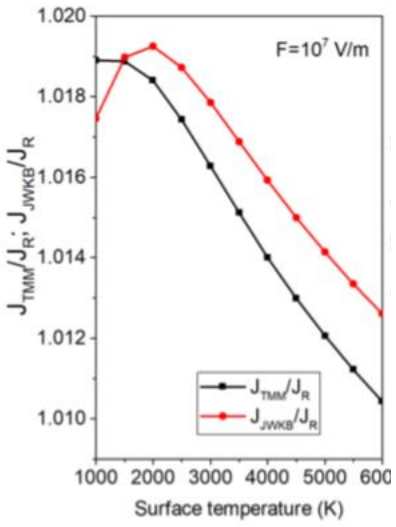



Fig. 4: *Transmission probability for electron emission without ion contribution at electric field of $10^9$ and $10^{10}$ V/m obtained by means of the TMM method and the JWKB approximation. $V_0$=11.2 eV, $y$=1$a_0$.*

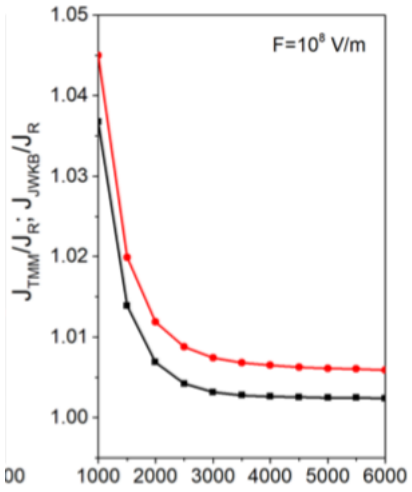
**UNIFIED TRANSFER MATRIX EVALUATION OF THE EMISSION CURRENT DENSITY FROM NON-REFRACTORY CATHODES OF ELECTRIC ARCS**

M. BAEVA

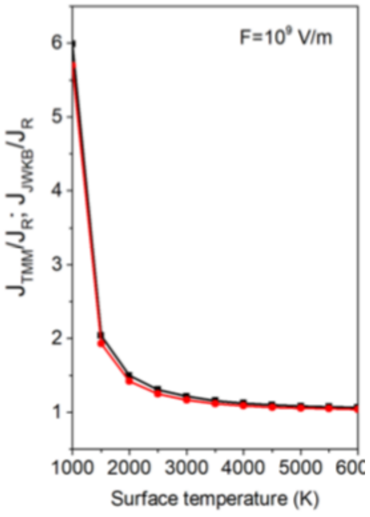
## Autres résultats :



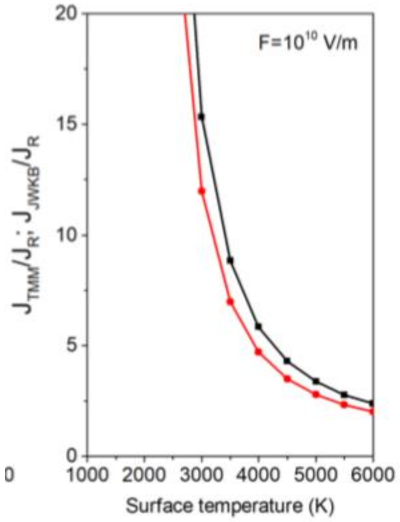

Ratio proche de 1




Ratio proche de 1




Ratio différent de 1




Grosses différences

### Conclusions :

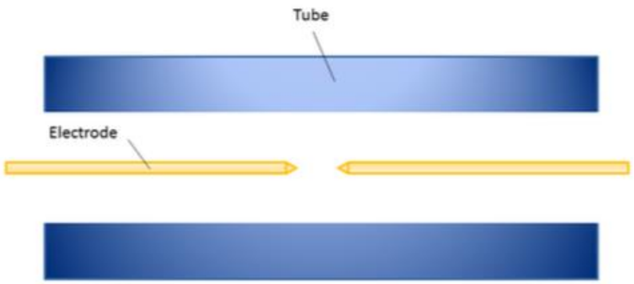
TMM marche à faible champ électrique

TMM peut être utilisée pour le développement des modèles de gaines de cathodes froides

# EFFECTS OF ENCLOSURE WALL MATERIAL ABLATION ON ARC VOLTAGE-CURRENT-CHARACTERISTICS

M. MUERMANN, H. NORDBORG, M. SCHUELLER, A. CHUSOV

**Objectif :** comprendre l'ablation des matériaux pour trouver de nouveaux matériaux et augmenter ainsi la capacité de coupure en HV




**Etude :** Expérimentale + simulation (sur Star-CCM+)
Etude de l'ablation avec des tubes en caoutchouc (rubber)
Le rayonnement est le mécanisme de transfert de chaleur principal

**Expériences :**
$\phi_{tube}$=1cm, L=10cm, gap=1cm
Dedans l'électrode est en cuivre

Couplage circuit oscillant à 15kV, 50Hz
Après claquage, mesure 500kHz
Tests avec tubes en céramique (témoins) & tube rubber

**Mesures :**
Mesure de la tension et du courant
Mesure de la masse du tube après plusieurs arcs

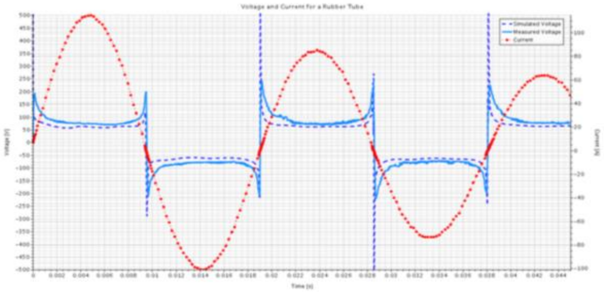


Fig. 6: *Voltage and current characteristics for a ceramic tube.*

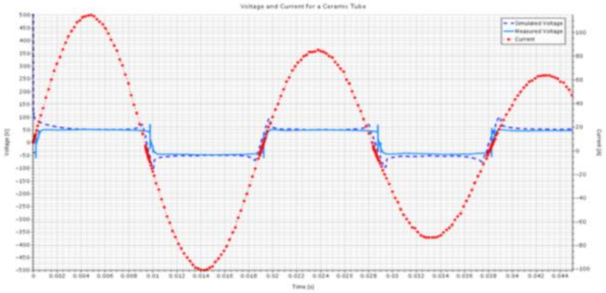
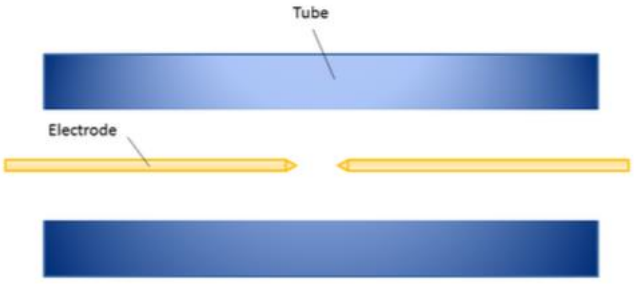


Fig. 7: *Voltage and current characteristics for a rubber tube.*

- Comparaison $V_{mesurée}$ et $V_{modèle}$
- Influence de la nature du tube sur V
- Dans le « ruber » tube, atteinte de l'équilibre thermique est plus longue

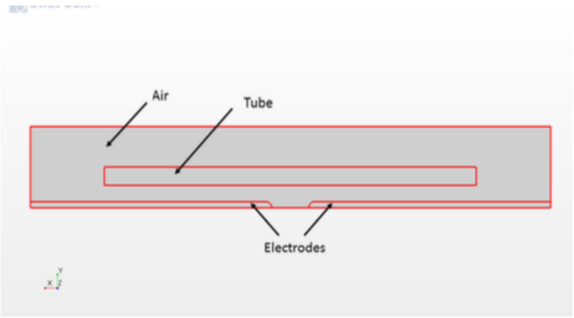
# EFFECTS OF ENCLOSURE WALL MATERIAL ABLATION ON ARC VOLTAGE-CURRENT-CHARACTERISTICS

M. MUERMANN, H. NORDBORG, M. SCHUELLER, A. CHUSOV




**Modèle numérique :**

Modèle 2D axi, laminaire, compressible, multi-espèces, air plasma
Méthode des volumes finis (Star-CCM+)
Prise en compte du rayonnement seul (DOM sur 2 bandes)
Prise en compte de l'érosion du cuivre (flux érosion contact : $30.10^{-9}$ $kg.C^{-1}$)
Prise en compte du potentiel électrique
Conductivité électrique = f(T, P, ablation wall, érosion cuivre)
Mixing rules – wall considéré comme du PA66 (pour les propriétés)
Taux érosion arc : $0.5 kg.m^{-2}.s^{-1}$



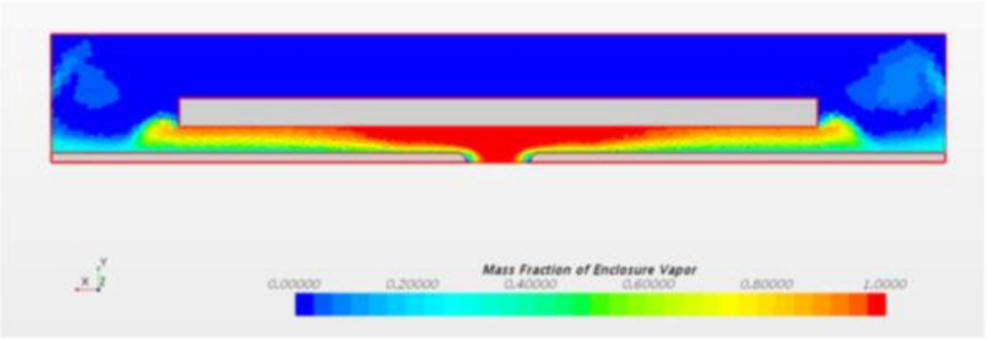




Fig. 10: *Mass Fraction of Enclosure Vapor at the end of the simulation.*

**Conclusions:**

Les approximations faites dans le modèles limitent les résultats mais reproduisent le bon comportement de l'arc

-> développements à améliorer

# MODELLING OF NOZZLE ABLATION IN GAS-BLAST CIRCUIT BREAKERS CONSIDERING ITS ACCUMULATIVE EFFECT DUE TO GEOMETRIC VARIATION

W. Wang, Xiaomin Zhao and J. D. Yan

**Etude :** ablation de la tuyère dans un disjoncteur à gaz comprimé
Etude de la modification de la tuyère (ablation par rayonnement) sur la capacité de coupure
Etude numérique - modélisation

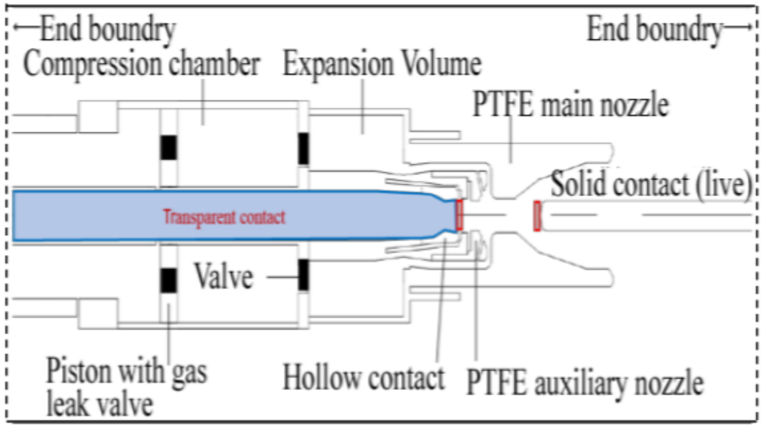



*Figure 1 Schematic diagram of the 145 kV/40 kA self-blast circuit breaker under investigation. The two red rectangles in front of the contact tips represent the transparent arc roots used in the model.*

Gaz $SF_6$, pression de 0.6MPa
Température de 300K
V/I : 145kV / 40kA

## Modèle:

Sur PHOENICS 3.6.1
Modèle 2D axi, turbulent Prandtl
LTE+LCE
+ PTFE masse concentration

$$m_{PTFE} = \frac{f}{h_{v,PTFE}}$$

$$f = (1-\alpha)\left(\int_0^{R_{83}T_{max}} q2\pi r dr\right)\xi$$

where $q$ is the net radiative power loss per unit volume determined from the radiation model, $\xi$ a coefficient which depends on $z$ and converts the radial radiative flux into a flux normal to the nozzle surface.

*Table 1 Source terms and diffusion coefficients for arc flow governing equations.*

| Equation | $\phi$ | $\Gamma_\phi$ | $S_\phi$ |
|---|---|---|---|
| Mass | 1 | 0 | 0 |
| Z-momentum | $w$ | $\mu_l + \mu_t$ | $-\frac{\partial P}{\partial z} + J_r B_\theta$ + viscous terms |
| R-momentum | $v$ | $\mu_l + \mu_t$ | $-\frac{\partial P}{\partial r} - J_z B_\theta$ + viscous terms |
| Enthalpy | $h$ | $\frac{\lambda_l + \lambda_t}{c_p}$ | $\sigma E^2 - q + \frac{dP}{dt}$ + viscous dissipation |
| PTFE mass concentration | $c_m$ | $\rho(D_l + D_t)$ | 0 |
| Current continuity | $\varphi$ | $\sigma$ | 0 |

PTFE en vapeur à 3400K (11.9MJ/kg)
PTFE density 2.2g/cm3

# MODELLING OF NOZZLE ABLATION IN GAS-BLAST CIRCUIT BREAKERS CONSIDERING ITS ACCUMULATIVE EFFECT DUE TO GEOMETRIC VARIATION

W. Wang, Xiaomin Zhao and J. D. Yan

## Résultats

Succès : test A, $t_{arc}$=13.6ms, RRRV 8.51kV/µs

Echec : test B, $t_{arc}$=12.3ms, RRRV 9.82kV/µs

Echec: test C, $t_{arc}$=20.1ms, RRRV 5.10kV/µs

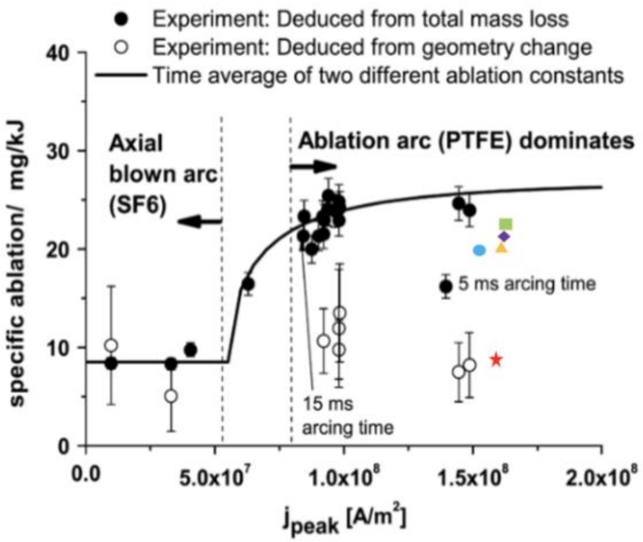



*Figure 3 Specific ablation obtained for a model circuit breaker [5] versus peak current density. The predicted and measurement specific ablations in the present work are also given. Triangle for Test A; Circle for Test B; Square for Test C. Diamond for prediction for all three cases; and Star for measurement.*

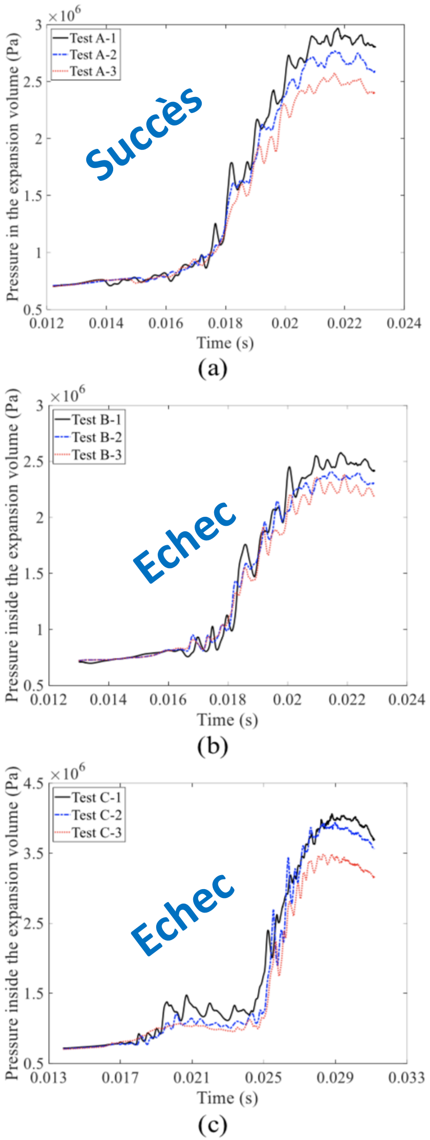



*Figure 5 Pressure distribution inside the expansion volume with the consideration of nozzle enlargement, (a) Test A; (b) Test B; (c) Test C. "1, 2, 3" represents the repeating cases.*

*Table 2 Predicted mass loss and the changed nozzle throat diameter with considering the enlargement of nozzle throat after each test.*

| Nozzle | Predicted mass loss (g) | | | Throat radius (mm) | | |
|---|---|---|---|---|---|---|
| | A | B | C | A | B | C |
| Main | 0.31 (23%) | 0.14 (18%) | 3.34 (65%) | 10.6 | 10.6 | 11.6 |
| Auxiliary | 1.50 (77%) | 1.21 (82%) | 1.55 (35%) | 10.6 | 11.4 | 12.4 |

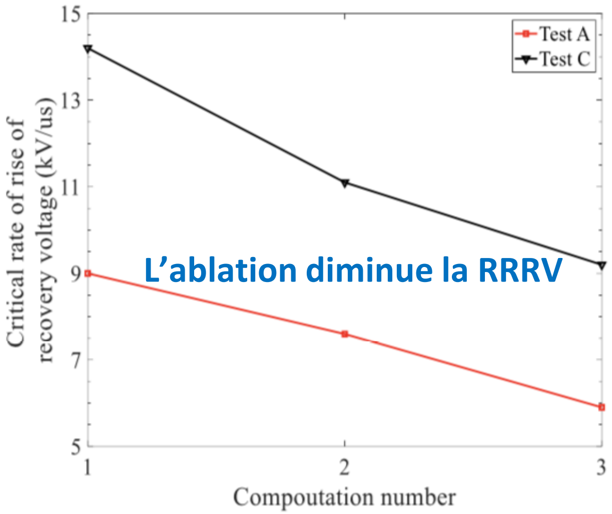



*Figure 6 Predicted variation of the RRRV when interruption is repeated under identical conditions with consideration of nozzle enlargement due to ablation.*

# AN INVESTIGATION OF DYNAMIC EROSION PROCESS OF ELECTRODES BY HIGH-SPEED IMAGING TECHNIQUE

YI WU, YUFEI CUI, MINGZHE RONG, HAO SUN, JIAWEI DUAN

**Etude :** de l'érosion par caméra rapide + illumination par laser proche IR (808.2nm) pour éclaircir la surface
+ visualisation de la morphologie de la surface de l'électrode et mesure du taux d'érosion en fonction du temps
+ Particle tracking velocimetry (PTV): distributions des trajectoires et des vitesses

**Expérience :** air, V=390VDC, I=400A, $\phi_{électrode}$= 5mm, $d_{électrodes}$= 8mm, CuW (30%Cu) ou $CeO_2W$ (1.8%$CeO_2$)
5x5 Laplacian mask pour éliminer la longueur de l'arc et détecter les bords des gouttes
Comparaison en fonction des matériaux des phénomènes aux électrodes, érosion par pulvérisation, attachement de l'arc, distribution des vitesses (de 100A à 400A), taux d'érosion.

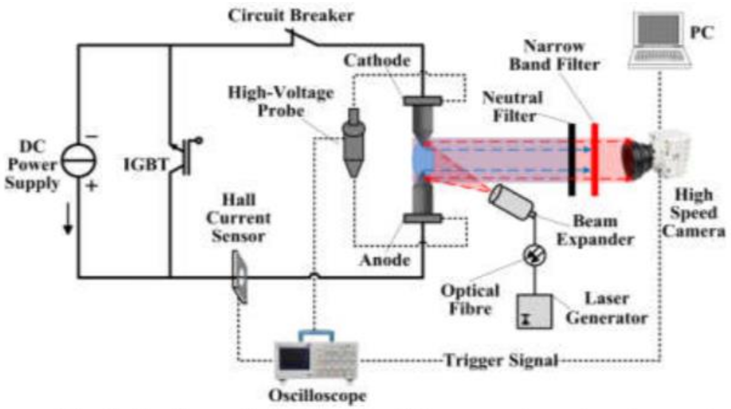



*Fig.1 A schematic diagram of the experiment system set-up.*

*Méthode PTV*
*identifications, vitesse et trajectoire des gouttelettes*

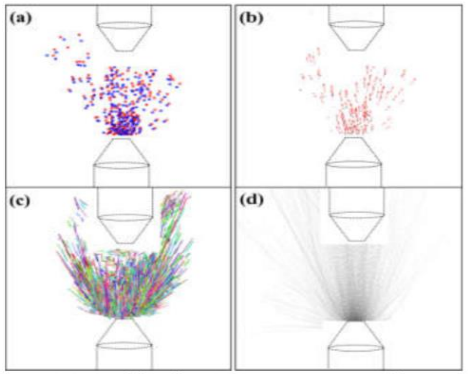



*Fig.3 (a) Recognition of droplets in two consecutive frames. (b) Velocity vectors detected by PTV. (c) Lagrangian trajectories of tungsten-copper droplets traced by PTV. (d) Original trajectories of droplets of tungsten-copper alloy.*

*2 pics discontinuité » : goutteles venant du bain de fusion*
*Autres pics : explosion de bulles en surface*

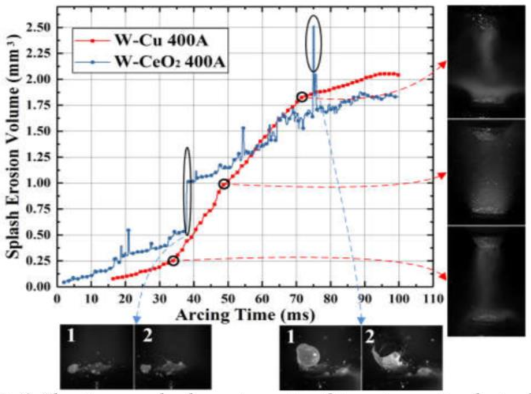



*Fig.9 The time-resolved erosion rate of tungsten-ceria electrodes and of tungsten -copper electrodes.*

**Conclusions : l'érosion de l'électrode est influencée par la fusion et le jet du plasma, elle peut être réduite par un contrôle du jet et de nouveaux matériaux pour les électrodes**

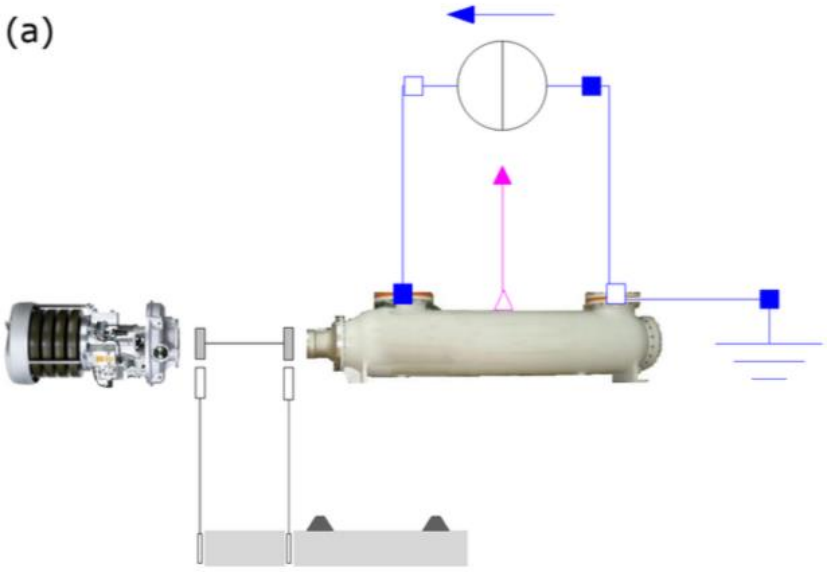
# SYSTEMS MODELING OF HIGH-VOLTAGE GAS-INSULATED CIRCUIT BREAKERS

J. LEHMANN, C. REUTLINGER, S. KOTILAINEN

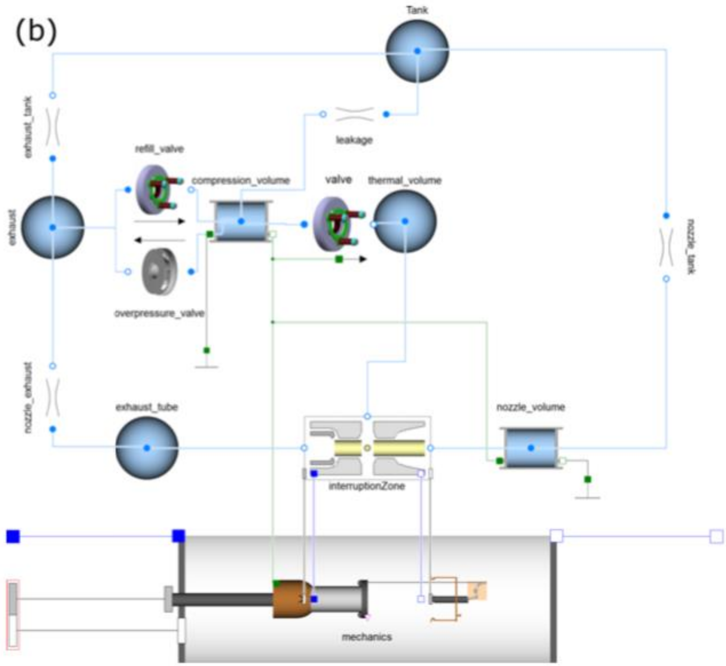
**Etude :** montée en pression dans un HVCB due à l'érosion

**Objectif :** optimisation de la géométrie/design du disjoncteur

Modélisation numérique




*(a) Top-level systems model for an HV circuit breaker (center) actuated by a hydro-mechanical drive (left) and interrupting a current source (top). The system is mechanically supported at the bottom. Electrical connections are shown in blue, mechanical ones in grey.*




*(b) Simplified model for breaker chamber consisting of a me- chanical block at the bottom, the interruption zone with the electrical arc in the center connected to various volumes, nozzle and valves. The color code of the connections is as in panel (a) except that addi- tionally connections for the 1d translational mechanics couplings of the pressure force are indicated in green.*

# SYSTEMS MODELING OF HIGH-VOLTAGE GAS-INSULATED CIRCUIT BREAKERS

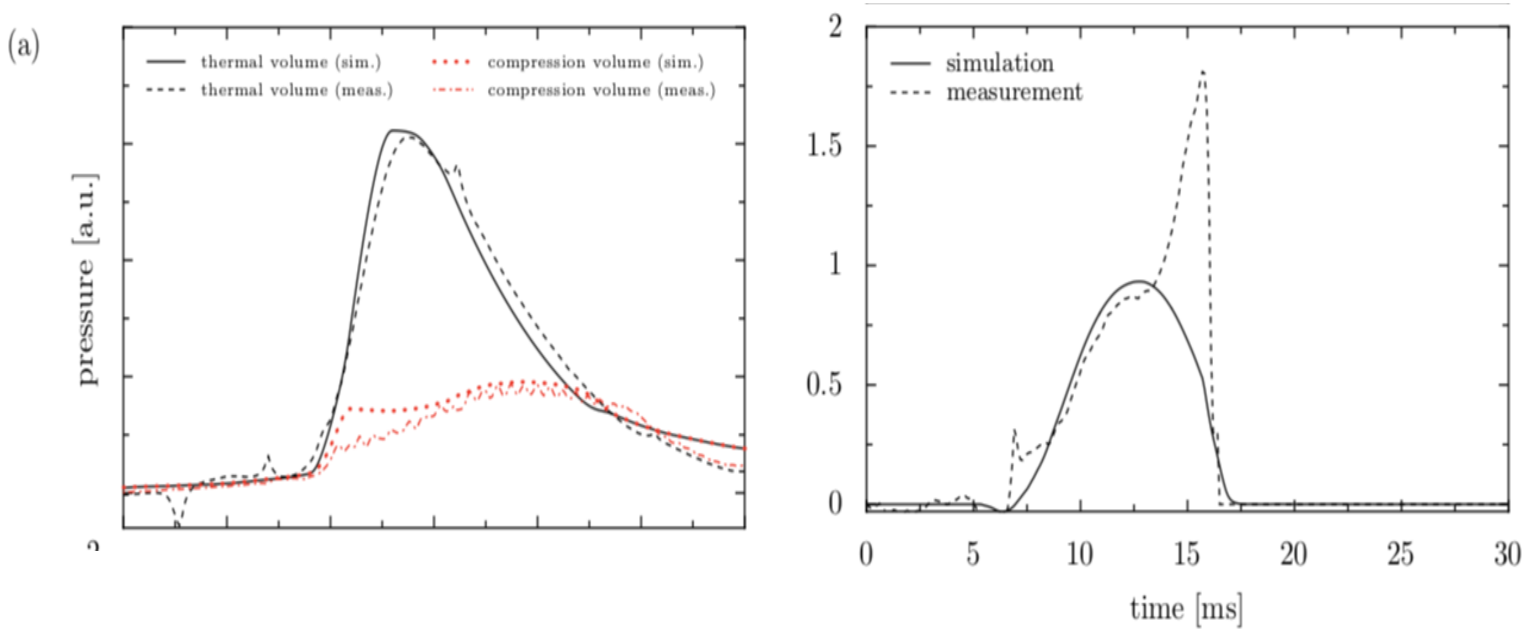
J. LEHMANN, C. REUTLINGER, S. KOTILAINEN

**Equations du modèle :**

**-** Gaz $CO_2$ (+$C_2F_4$)

- Propriétés thermodynamiques + propriétés de transport par loi de wilke
- Cylindrique, énergie en $\varepsilon.\sigma.T^4$ ($\varepsilon$ pour représenter la ré-absortion du rayonnement dans la colonne de l'arc)

## Validation sur le $CO_2$




*Reproduction of (a) the pressure buildup and (b) the arc voltage in development tests for a $CO_2$ circuit breaker. The mea- sured data for position of the drive and current are used as inputs to the simulations. Note that before current interruption, the mea- sured arc voltage shows the so-called extinction peak, which is not reproduced in our arc model for the high current phase.*

## Exemple d'optimisation pour le $SF_6$

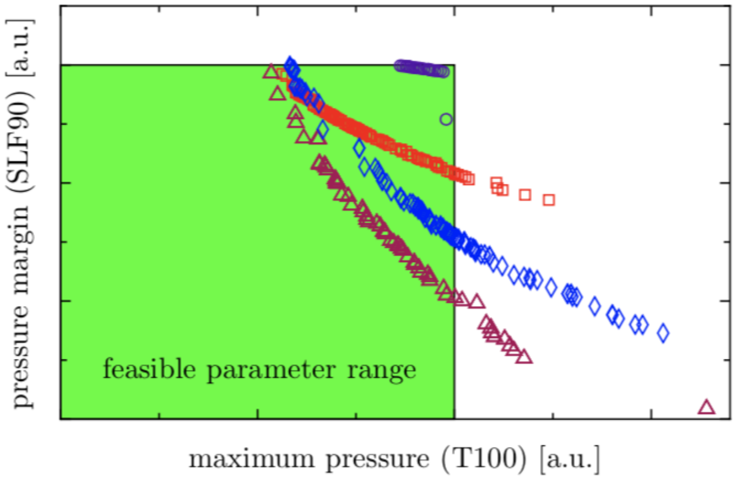



Fig. 4: *Results of a multi-objective optimization for the design of an $SF_6$ circuit breaker. Pareto fronts show the trade-off between maximal pressure in T100 test duties and high interruption capability in SLF90 tests. The feasibility range is marked and each set of symbols corresponds to a single group of system designs for which geometrical parameters of the breaker are varied.*

## ARC VOLTAGE DISTRIBUTION MEASUREMENT IN A MEDIUM VOLTAGE ABLATION-DOMINATED SWITCH

H. TAXT, T. R. SETTENDAL AND K. NIAYESH

**Etude :** mesure de la tension dans différentes région (MV)

**Postulat :** σ n'est pas homogène le long de la colonne d'arc, d'où une étude dans différentes régions

**Méthode habituelle :** mesures de potentiels dans les différentes régions avec méthode non invasives: capteurs capacitifs (rôle sur arc en extinction), par estimation de la conductance dans les régions, **MAIS** nécessite de nombreux points pour une mesure avec capteurs capacitifs, une bonne résolution spatiale -> fastidieux

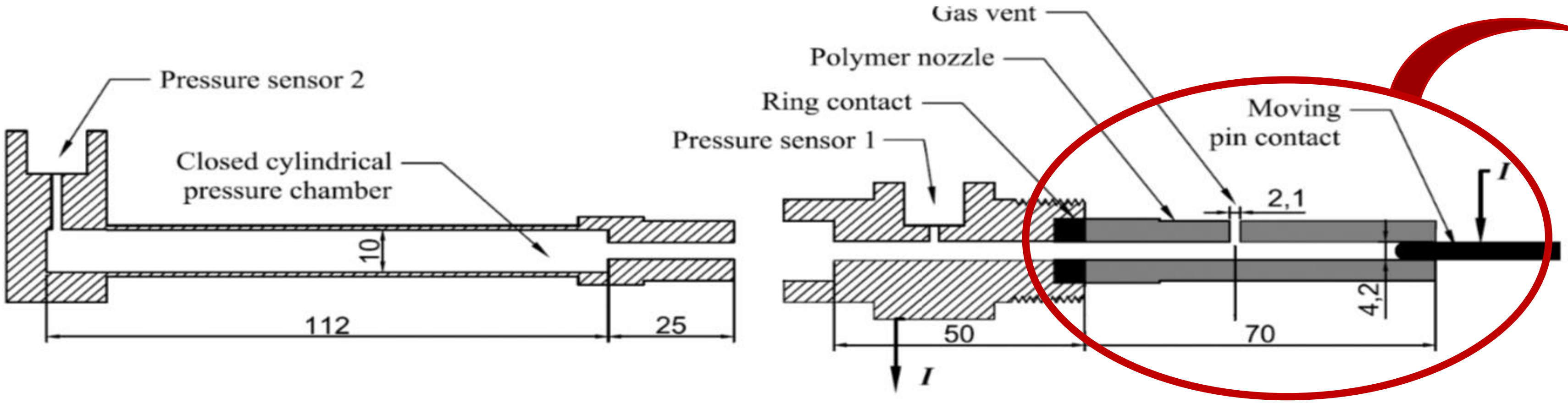



*Fig. 1 The test switch with 4-mm pin contact in open position on the right hand side. The part to the left can be attached to the switch, creating a closed volume that allows for the pressure to build up on the left-hand side of the electric arc. In the open configuration, this part is removed, so pressure can not build up. The contacts (solid black) are made of copper-tungsten and the main casing and pressure chamber (hatched parts) are made of brass. Current connection points are indicated by arrows, I. Dimensions are in millimetres.*

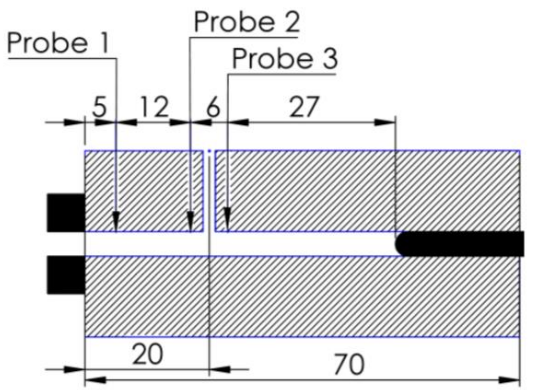



*Fig. 2 Modified PP nozzle with electric probes at three positions. The contacts are shown in solid black and the hashed area is the PP nozzle. Distances are given in millimetre.*

**Tests :** 6.9kV, 165$A_{rms}$, tube polypropylene (PP), mesure à 3 positions, un contact fixe, un mobile, tungsten wires pour mesure de V qui peut supporter 50μA à 5kV, on se place dans la zone vapeur nozzle (source d'erreur mais moindre).

# ARC VOLTAGE DISTRIBUTION MEASUREMENT IN A MEDIUM VOLTAGE ABLATION-DOMINATED SWITCH

H. TAXT, T. R. SETTENDAL AND K. NIAYESH

**Méthodes :**

Mesures directes avec galvanic contact de l'arc, peu de points sont nécessaires

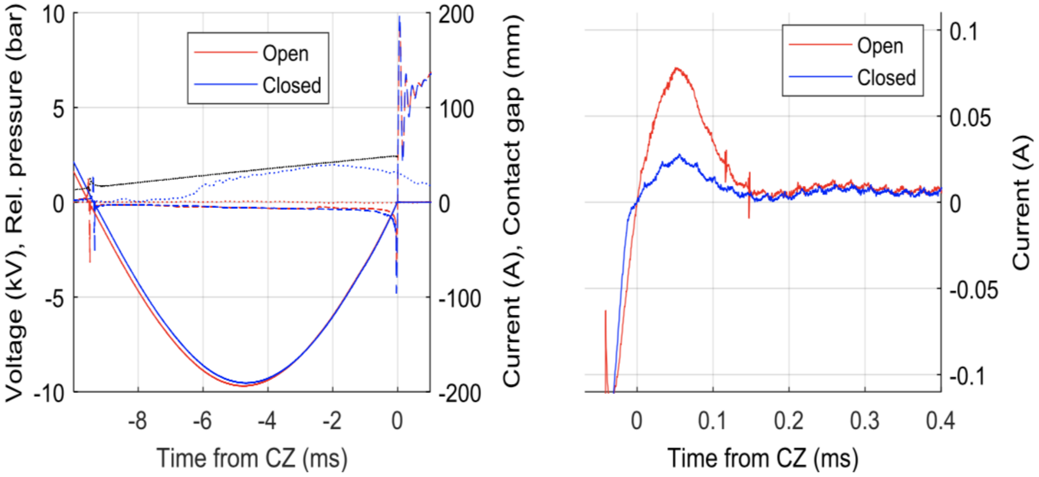



*Fig. 3 Current (solid), voltage (dashed) and pressure (dotted) measurements of interruptions in the open and closed volume case. The nearly straight, black line is the contact separation in millimetre. The post-arc current is shown in detail to the right.*

En position fermée : $I_{coupure}$ à 3.2A, V=4.8kV

En position ouverte : $I_{coupure}$ à 2.4A, V=3.4kV

Coupure : augmentation rapide du gap contact (surtout en position ouverte)

1/ Changement important de $V_{arc}$ et de sa distribution quand on passe de ouvert -> fermé

2/ $V_{arc}$ à l'extinction (environ 30µs avant CZ) est supérieur au cas fermé

3/ 0.4 ms avant CZ : 420V (ouvert), 650V (fermé)

4/ Après extinction arc : champ E uniforme sur l'axe de l'arc

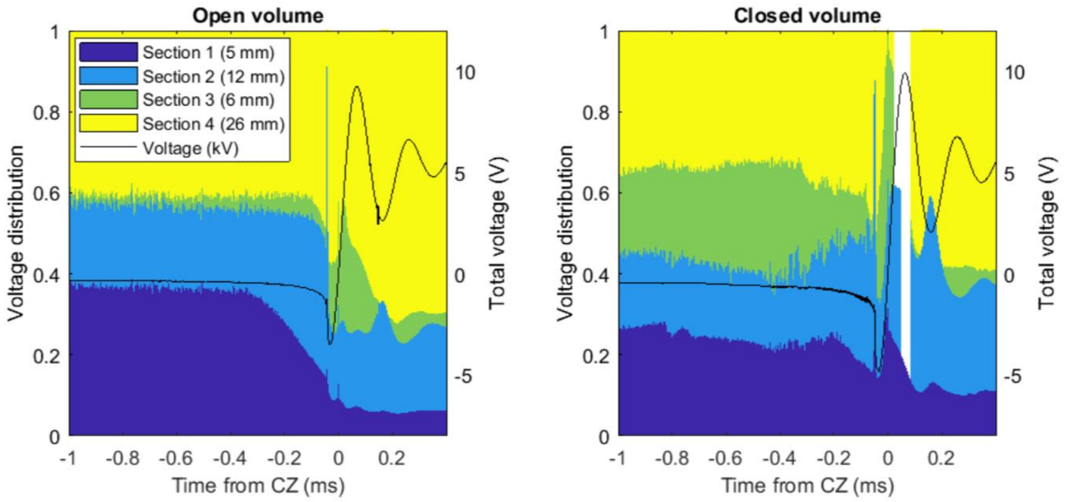



*Fig. 4 Voltage distribution in the open and closed volume case. The probe voltage measurements are missing for a short period because the voltage excided the measuring range of ± 5 kV. The arc voltage 0.4 ms before CZ is 420 V in the open case and 650 V in the closed case.*

# WORKSHOP on Ablation interaction arc-materials

*Mikhail S. Benilov : Recent advances in simulation of plasma-electrode interaction in arc discharges*

*Margarita Baeva : The bidirectional electrodes-plasma interaction as indispensible part of advanced arc plasma modelling*

*Yasunori Tanaka : Spallation occurrence from polyamide materials exposed by thermal plasma*

*Joseph D. Yan : Inclusion of nozzle dimensional change due to PTFE ablation in switching arc simulation*

*Philippe Robin-Jouan : Ablation modelling in High Voltage circuit-breakers: impact on the arc extinction*

*Simon Marek : Evaporation-based model for plasma-cathode attachement in GMA welding*

## 1.Challenges/requirements in a state-of-the-art modelling of arc plasma (TIG arcs as example)

→ Bidirectional interaction between arc plasma and electrodes

## 2.Advanced model of TIG arcs including the bidirectional interaction between the electrodes and the plasma

→ Bidirectional plasma-electrode interaction – the electric power generated in the space-charge sheath goes not only to the cathode to heat it and ensure thermionic emission but a part of it heats the plasma electrons

## 3.The power balance of the TIG arc as an illustration

→ The model must be capable of predicting both **temperature** and **arc voltage, heat loads on the electrodes**

Arc power balance shows the importance of accounting for the bidirectional interaction between the electrodes and the arc plasma

~ 40%-50% of the electric power is deposited in the cathode sheath **-> significant sheath voltage -> arc voltage**

~ 28%-43% of the power in the cathode sheath is going to the plasma electrons **-> electron temperature**

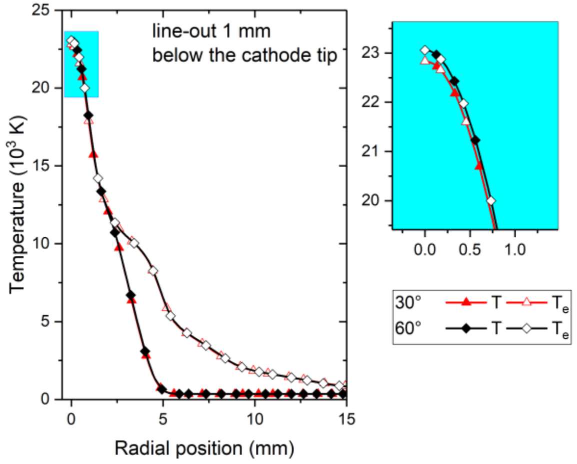
- the rest power is heating the cathode **-> heat loads on the electrode**

## 4.Other effects of the bidirectional interaction

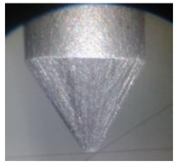
→ effect of cathode shape on plasma temperature

effect on Temperature and normal current density on the cathode surface

effect on Normal component of density of electron energy flux at the cathode




30°



60°

## 5.Concluding remarks

## Constats :

**1/ Polymer materials are widely used for an insulator in low voltage circuit breakers, arcing hornsand for a gas flow nozzle in high-voltage circuit breakers.**

**2/ In a current interruption process, the arc plasma is formed between the electrodes in the circuit breaker. The arc plasma may contact the polymer materials, inevitably involving polymer ablation.**

**3/ The polymer ablation can generate pressure rise, cooling and shrinkage of arc plasma. It may enhance the arc interrupting capability of the circuit breaker.**

**Objective:** Fundamental investigation on thermal interaction between polymer material and thermal plasmas for LV-CB

### Experimentals

ICTP exposure to polymer specimens

**-Observation of C2emission spectra in ablated vapor**

**-Estimation of temperature decay by polymer ablation**

### Numericals

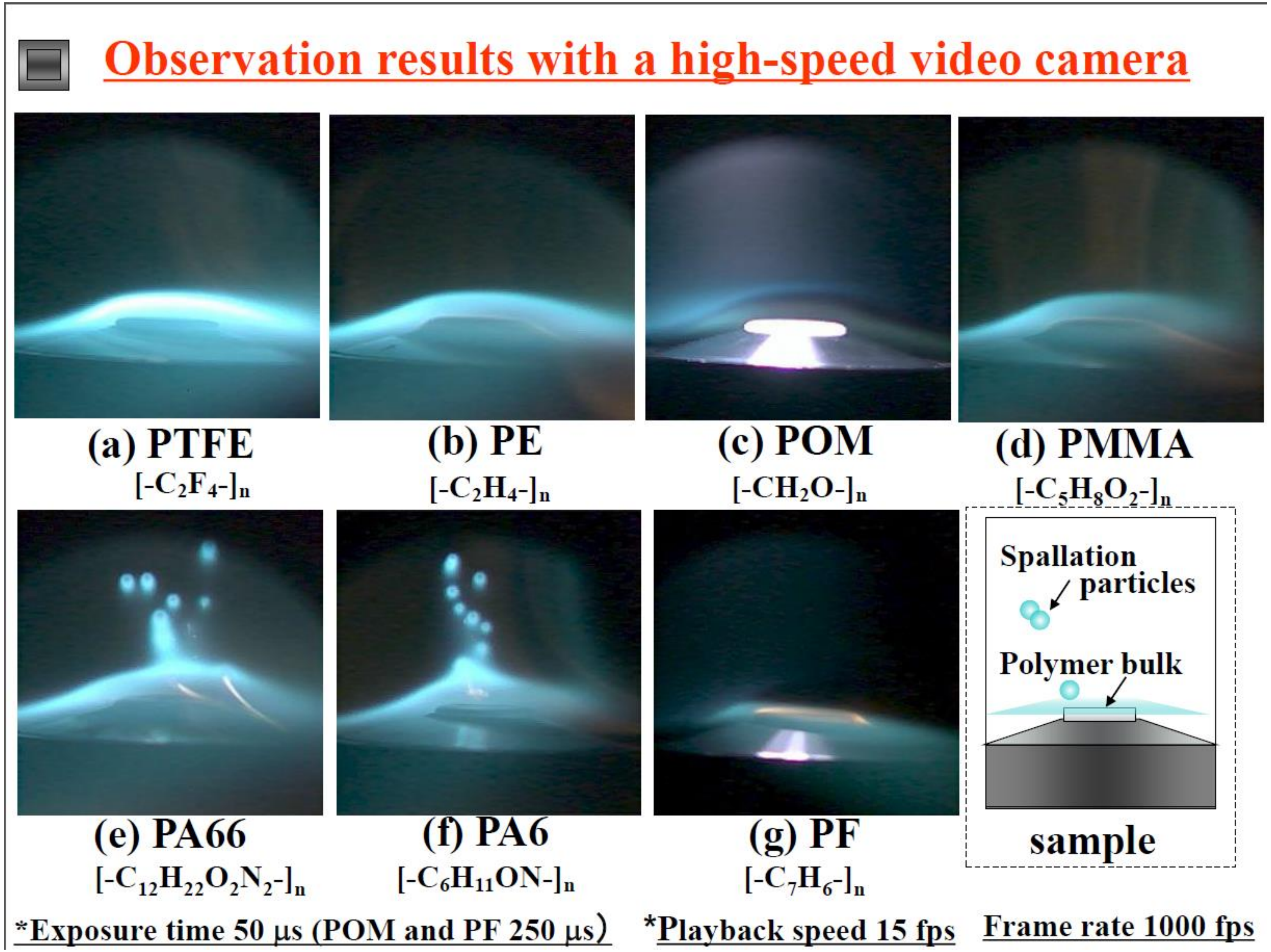
Modeling of thermal interactions **between plasma-polymers.**

**-Prediction of temperature decay by polymer ablation**

**-Mixing of ablated vapor**

**-Effect of vapor properties**

## Experimentals

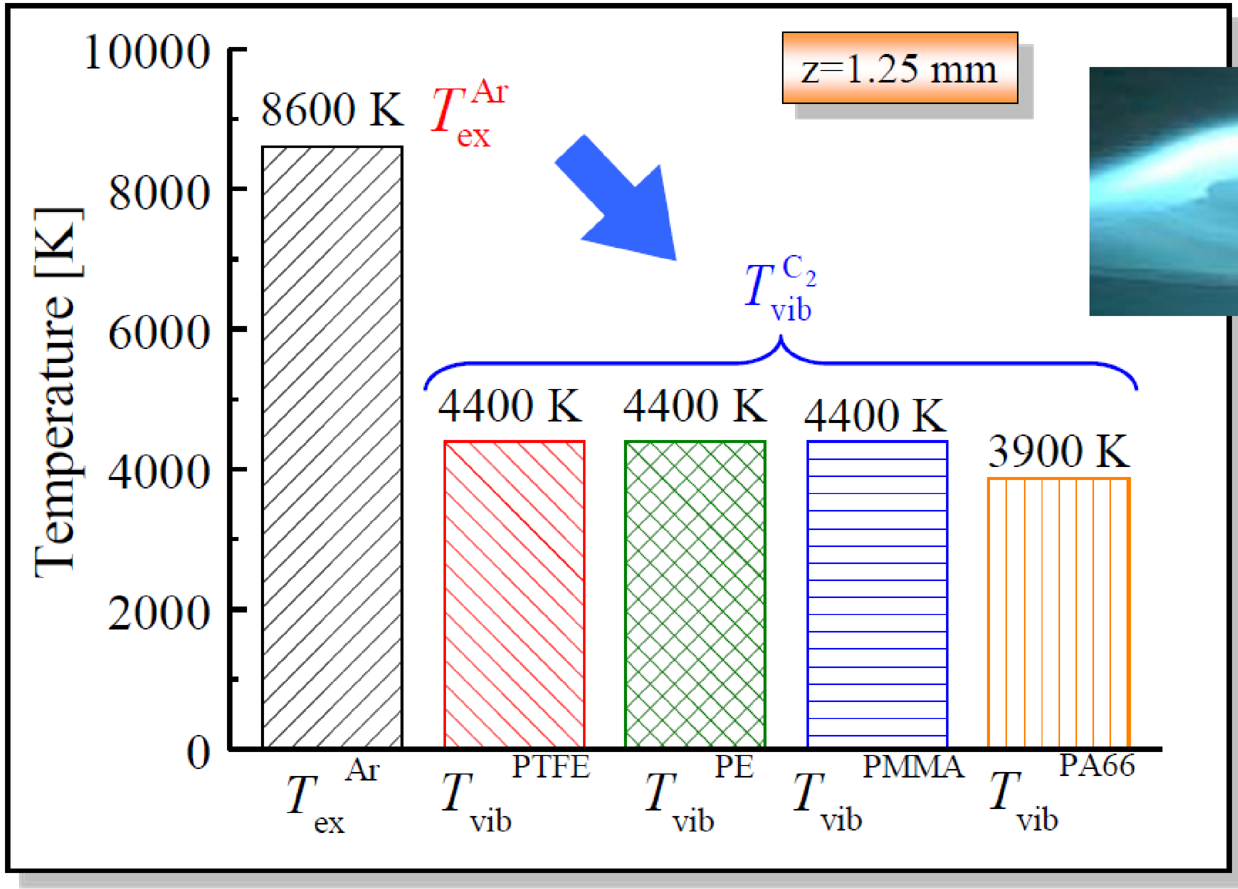


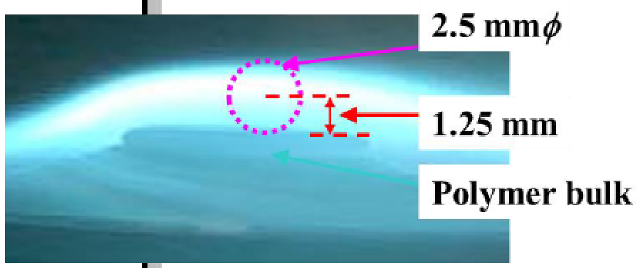
**Experimentals**

# Temperature at z=1.25 mm from the surface

$T_{ex}^{Ar}$, $T_{vib}^{C_2}$ are close to electron temperature under the present condition.

→ These can be compared with each other.

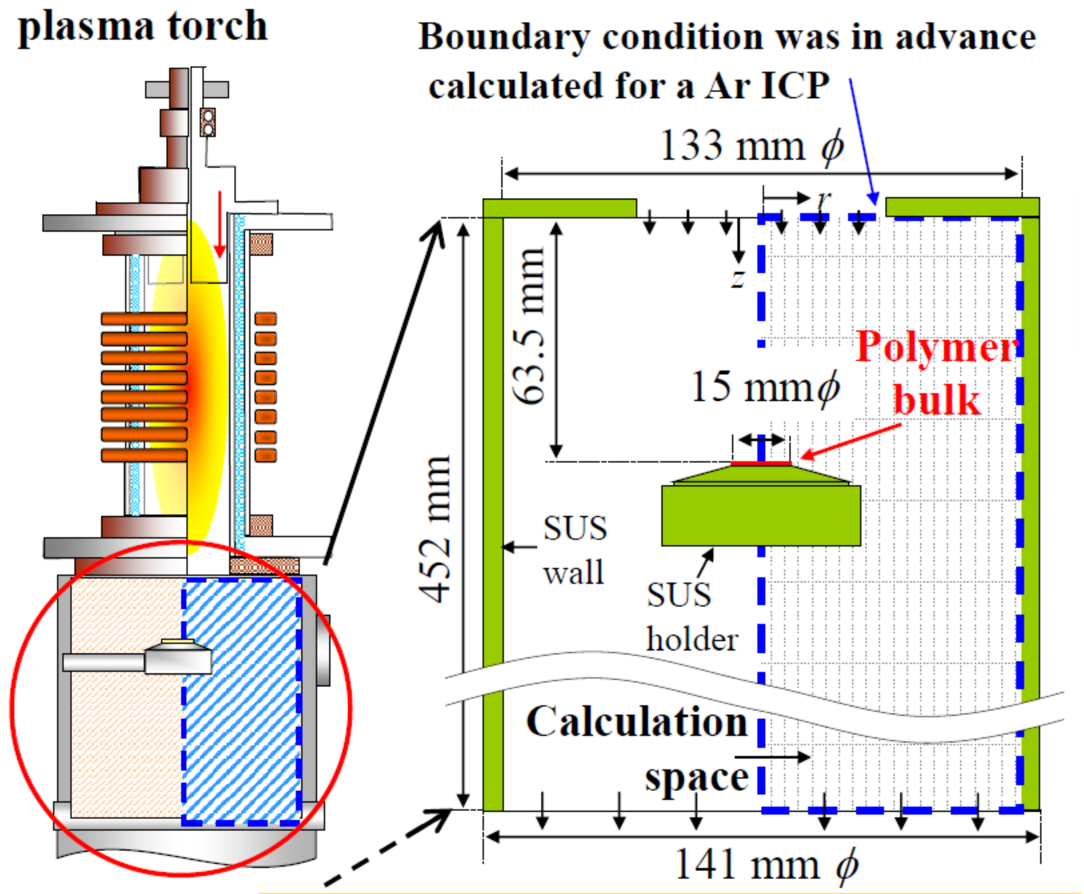



Temperature of ablated vapor is almost independent of polymer kinds.

**Temperature decay due to polymer ablation** =about 4000 K

## Numericals

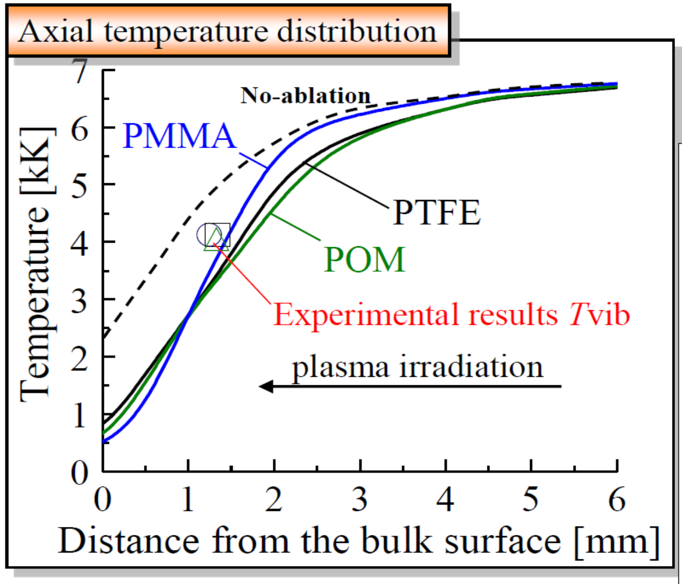


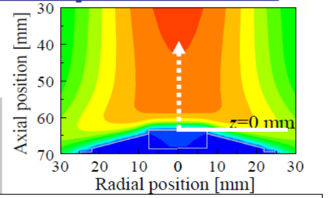

**Calc.cond.**

| | |
|---|---|
| Input power | : 7.5 kW |
| Ar sheath gas | : 30 slpm = (liters /min) |
| Pressure | : 760 torr |
| Polymer | : PTFE, PE, POM |

**Mass conservation**
**Momentum conservation**
**Energy conservation**
**Mass conservation for polymer ablated vapor**
**Mass source term from ablation**
**Mass flux by ablated vapor**

### Comparison in temperature between experimental and numerical results




- Polymer ablation leads to temperature decay around the surface of polymer specimens.
- The temperature decay is mainly due to energy consumption for dissociation and excitation of byproduct molecules.
- POM ablation causes larger temperature decay more upstream.
- Calculated results agree with experimental results at the meas. point.

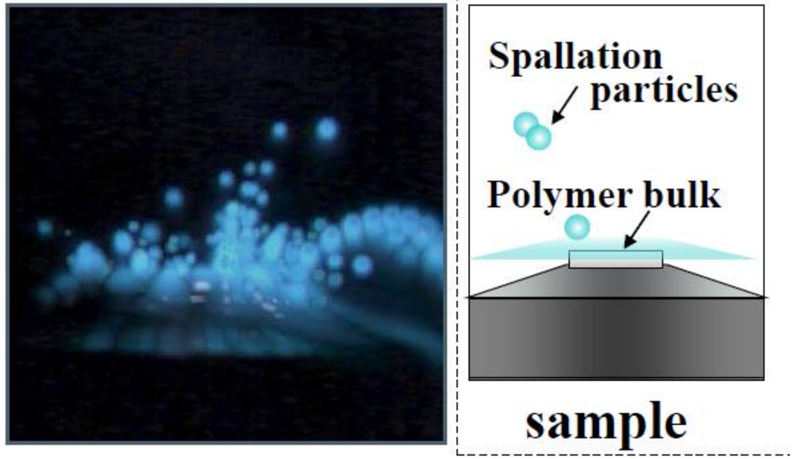
## Expected effects of spallation particles on arc plasmas

- **The spallation particles can penetrate more deeply to the arc plasma than ablated vapor itself. Ablation of these particles in the arc core can affect arc quenching much more.**
- **It is expected that effective utilization of such spallation phenomena can enhance the arc interrupting capability of circuit breakers**

**But, why does spallation particle ejection occur only from PA66 & PA6?**

**Thermoplastic polymer materials. They are widely used as films, synthetic polymers. They have the amide-bond.**
**→ which provides high water-absorption coefficient due to hydrogen bond.**

**PA66 w/water absorption shows not only ablated vapor but also many spallation particles definitely.**



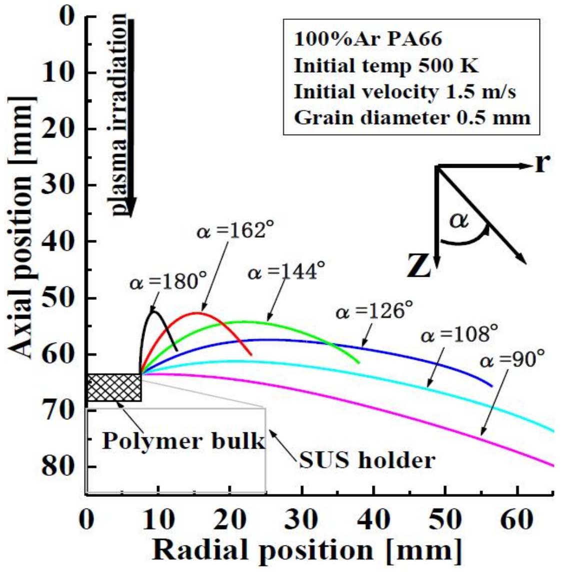
## Expected effects of spallation particles on arc plasmas

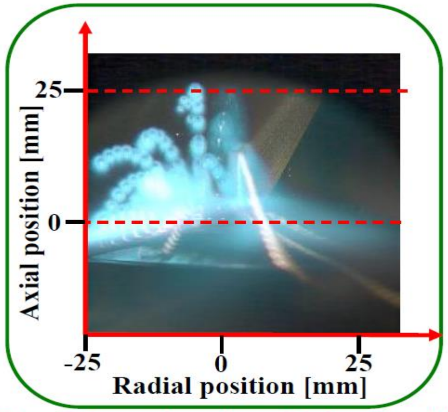
**Numerical approach *for the trajectory of spallation particle***

**Only the forces affecting an individual particle are Drag force and Gravity**

**We estimated that the spallation particles have initial sizes of 0.2-1.0 mm(ϕ) and initial velocities of 1.0-4.0 m/s (an initial energy of 1–100 nJ)**

**Spallation particle occurrence is related to high water-absorption coefficient of PA6 and PA66 due to Amide-bond. Spallation is promoted by $N_2/O_2$included plasma exposure.**




*The trajectories of spallation particles from PA66 bulk surface in the experiment*

⇒ Particles are rapidly evaporated by high heat flux from the thermal plasma.
⇒ The calculated trajectories are similar to the experiment results.