Fusion Data Science at Ghent University

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with thanks to
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Overview

1. Introduction: data science
2. Regression analysis for scaling laws
3. Probabilistic characterization of stochastic plasma phenomena
4. Sensor fusion
5. Anomaly detection and predictive maintenance
6. FUSION-EP joint master program

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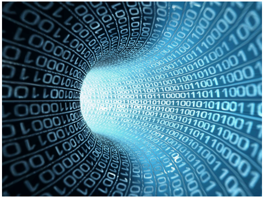
What is data science?

- Activities:
  - Data processing: cleaning, filtering, visualization, . . .
  - Optimization
  - Estimation, testing and prediction
  - Pattern recognition: clustering, regression analysis, dimensionality reduction



- Methods:
  - Probability theory
  - Statistics
  - Machine learning
  - Artificial intelligence
- Culture:
  - Best practices
  - Training
  - Community exchange

Foundations matter

- Performance in complex environments
- Robustness of methods and results
- Simplicity:
    - Explainable models
    - Minimal parameter tuning
    - Adoption in data-intensive communities

vs.

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Global H-mode confinement scaling in tokamaks

- Updated ITPA global H-mode energy confinement database (DB5.2.3):
  - New data closer to ITER conditions and expanded ranges
  - New data from devices with fully metallic walls
- Issues with IPB98(y,2):

Density scaling — Power degradation — No δ scaling

$$\tau_{\mathrm{E,th}} = 0.0562\, I_{\mathrm{p}}^{0.93}\, B_{\mathrm{t}}^{0.15}\, \bar{n}_{\mathrm{e}}^{0.41}\, P_{\mathrm{l,th}}^{-0.69}\, R_{\mathrm{geo}}^{1.97}\, (1+\delta)^{\alpha_\delta}\, \kappa_{\mathrm{a}}^{0.78}\, \epsilon^{0.58}\, M_{\mathrm{eff}}^{0.19}$$

$$\Omega_{\mathrm{i}} \tau_{\mathrm{E,th}} = 4.24 \times 10^{-7}\, \rho_*^{-2.69}\, \beta_{\mathrm{t}}^{-0.90}\, \nu_*^{-0.0081}\, q_{\mathrm{cyl}}^{-2.99}\, (1+\delta)^{\alpha_\delta}\, \kappa_{\mathrm{a}}^{3.29}\, \epsilon^{0.71}\, M_{\mathrm{eff}}^{0.96}$$

β degradation — No collisionality scaling — No δ scaling

Robust Bayesian regression

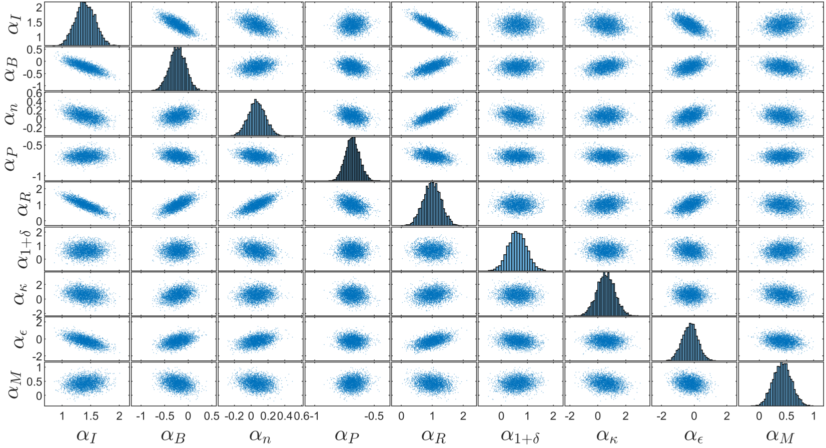
- Motivation:
  - Measurement uncertainty
  - Model uncertainty
  - Heterogeneity: multi-machine database
  - Errors in all variables
  - Multicollinearity: e.g. $I_{\mathrm{p}} \propto B_{\mathrm{t}}$
- Robust likelihood:

$$
\begin{aligned}
&p\left(\{y_{i_k,k}\},\{x_{i_k,j,k}\}\,|\,\{\alpha_0,\alpha_j\},\{\gamma_k\}\right)\\
&\qquad = \prod_k \prod_{i_k} \frac{1}{\sqrt{2\pi\gamma_k^2\sigma^2_{\mathrm{mod},i_k,k}}} \exp\left[-\frac{1}{2}\frac{\left(y_{i_k,k}-\eta_{i_k,k}\right)^2}{\gamma_k{}^2\sigma^2_{\mathrm{mod},i_k,k}}\right]
\end{aligned}
$$

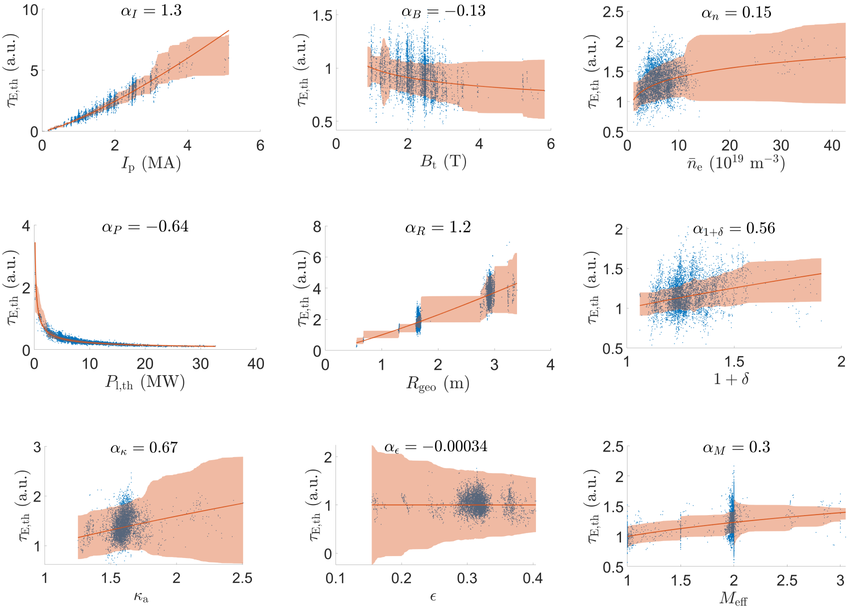
1 for each device

Practical error bars

- Model uncertainty: sensitivity analysis
- $\sim 10\times$ larger error bars



Trends



$\alpha_I = 1.3$
$\tau_{\mathrm{E,th}}$ (a.u.)
I_{p} (MA)
$\alpha_B = -0.13$
$\tau_{\mathrm{E,th}}$ (a.u.)
B_{t} (T)
$\alpha_n = 0.15$
$\tau_{\mathrm{E,th}}$ (a.u.)
$\bar{n}_{\mathrm{e}}$ (10^{19} m^{-3})
$\alpha_P = -0.64$
$\tau_{\mathrm{E,th}}$ (a.u.)
$P_{\mathrm{l,th}}$ (MW)
$\alpha_R = 1.2$
$\tau_{\mathrm{E,th}}$ (a.u.)
R_{geo} (m)
$\alpha_{1+\delta} = 0.56$
$\tau_{\mathrm{E,th}}$ (a.u.)
$1+\delta$
$\alpha_\kappa = 0.67$
$\tau_{\mathrm{E,th}}$ (a.u.)
κ_{a}
$\alpha_\epsilon = -0.00034$
$\tau_{\mathrm{E,th}}$ (a.u.)
ϵ
$\alpha_M = 0.3$
$\tau_{\mathrm{E,th}}$ (a.u.)
M_{eff}

Geodesic least squares

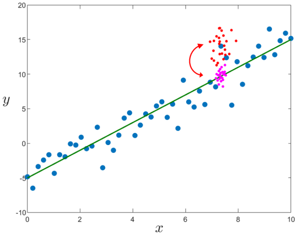
- Geodesic least squares: ***GLS***

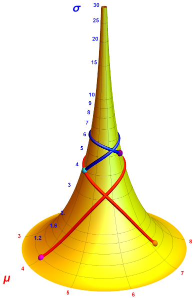
$$\prod_k \prod_{i_k} \frac{1}{\sqrt{2\pi\sigma^2_{\mathrm{tot},i_k,k}}} \exp\left[-\frac{1}{2}\frac{(y_{i_k,k}-\eta_{i_k,k})^2}{\sigma^2_{\mathrm{mod},i_k,k}}\right]$$

Rao geodesic distance (GD)

$$\frac{1}{\sqrt{2\pi}\,\sigma_{\mathrm{obs}}} \exp\left[-\frac{1}{2}\frac{(y-y_i)^2}{\sigma_{\mathrm{obs}}{}^2}\right]$$

G. Verdoolaege *et al.*, Nucl. Fusion, **55**, 113019, 2015
G. Verdoolaege *et al.*, Entropy, **17**, 4602–4626, 2015





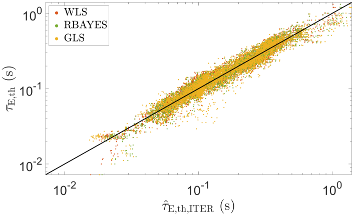
Multi-machine engineering scaling

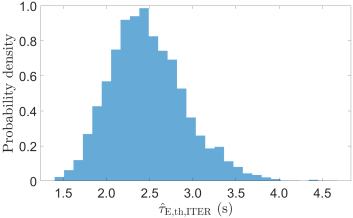
STD5-IL ELMy H-mode (error bars from Bayesian analysis)

Engineering scaling

$$\tau_{\mathrm{E,th}} = (0.067 \pm 0.060)\, I_{\mathrm{p}}^{1.29\pm0.17}\, B_{\mathrm{t}}^{-0.13\pm0.17}\, \bar{n}_{\mathrm{e}}^{0.15\pm0.10}\, P_{\mathrm{l,th}}^{-0.644\pm0.060}\, R_{\mathrm{geo}}^{1.19\pm0.29} \times (1+\delta)^{0.56\pm0.35}\, \kappa_{\mathrm{a}}^{0.67\pm0.65}\, M_{\mathrm{eff}}^{0.30\pm0.17} \quad \rightarrow \mathbf{H_{20}}$$

$$\hat{\tau}_{\mathrm{E,th,ITER}} = 2.79 \pm 0.44\,\mathrm{s}$$





G. Verdoolaege *et al.*, Nucl. Fusion, **61**, 076006, 2021

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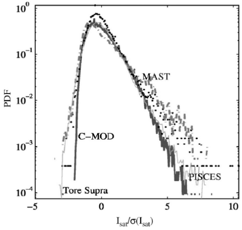
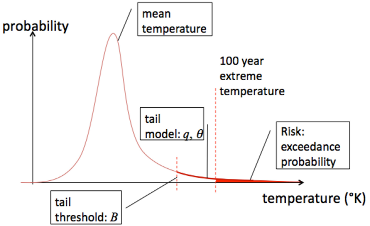
Why a probabilistic approach?

- Quantify and compare uncertainty, variability, fluctuations
- Physical information from distributions



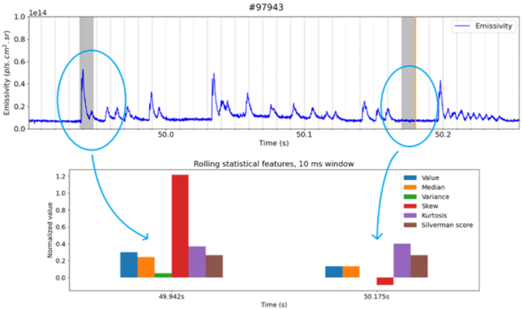
I. Sandberg *et al.*, Phys. Rev. Lett. **103**, 165001, 2009

- Risk analysis, extreme events



Edge-localized modes

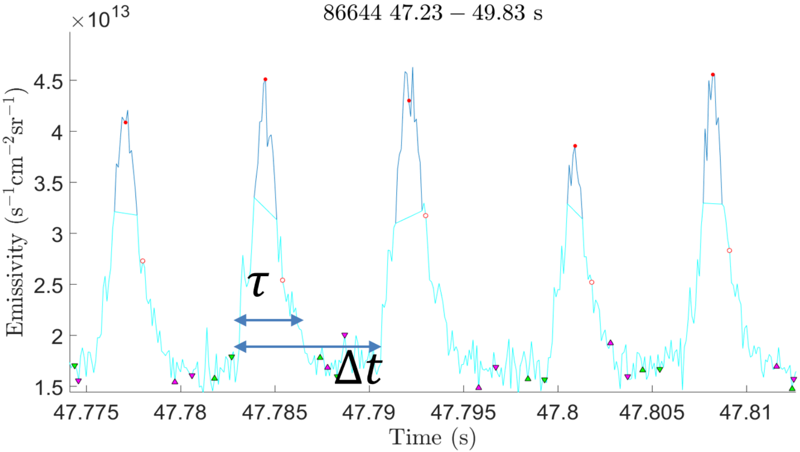
- Distributions of ELM characteristics
- Dependence of distributions on plasma conditions



	Results	
	TP (%)	FP (%)
Optimal threshold	34.41	17.53
Laplacian of Gaussian	86.61	12.79
Deconvolution	78.14	70.30
Rolling z-score	89.99	16.39
Convolution NN	80.01	16.63
Recurrent NN	91.95	15.90

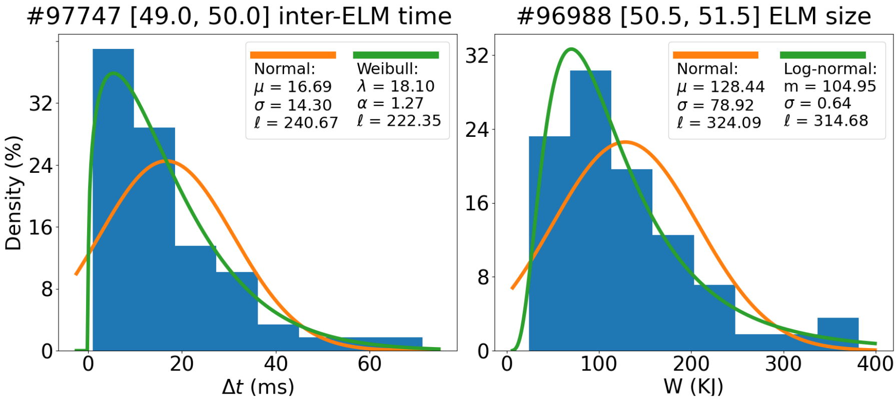
J. Alhage et al., in preparation, 2024

ELM timing



86644 47.23 – 49.83 s
×10^13
Emissivity (s^−1cm^−2sr^−1)
4.5
4
3.5
3
2.5
2
1.5
47.775
47.78
47.785
47.79
47.795
47.8
47.805
47.81
Time (s)
τ
Δt

Inter-ELM time Δt



J. Alhage et al., in preparation, 2024

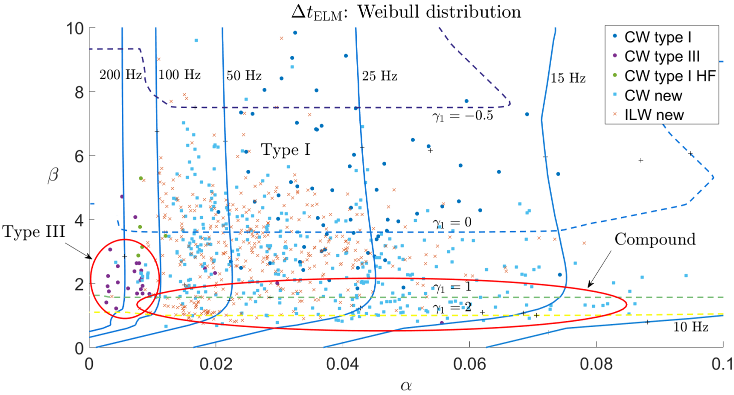
Shifted Weibull distribution:

$$p(t) = \frac{\beta}{\alpha}\left(\frac{t - t_{\mathrm{m}}}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t - t_{\mathrm{m}}}{\alpha}\right)^{\beta}\right], \qquad t > t_{\mathrm{m}}$$

A.J. Webster *et al.*, Phys. Rev. Lett. **110**, 155004, 2013

Distribution map Δt_{ELM}

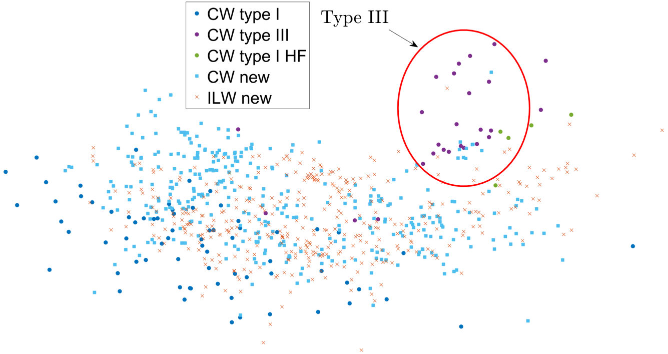
- 453 plasmas from JET carbon wall
- 379 plasmas from JET ITER-like wall
- 100 reference plasmas (A. Shabbir *et al.*, Rev. Sci. Instrum. **87**, 11D404, 2016)

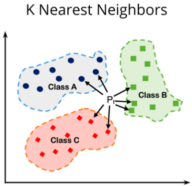


G. Verdoolaege et al., 45th EPS Conference on Plasma Physics, ECA **42A**, P.1078, 2018

Projected map Δt_{ELM}

Approximately isometric projection with multidimensional scaling:

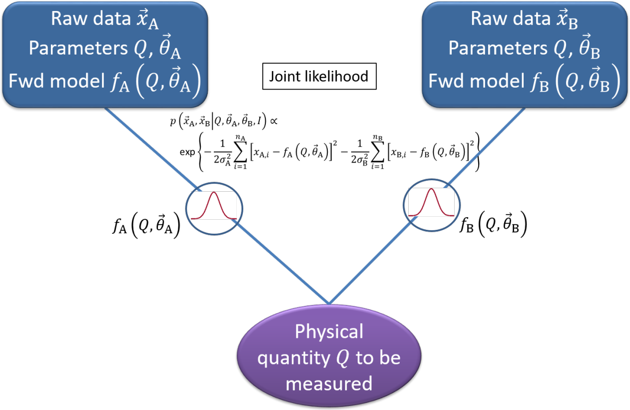




Overview

Sensor fusion

- Sensor fusion / Data fusion / integrated data analysis (IDA)

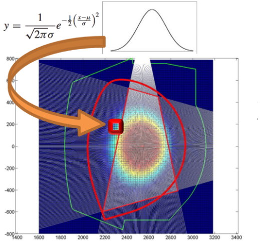


$$\underbrace{p(Q, \boldsymbol{\theta}_{\mathrm{A}}, \boldsymbol{\theta}_{\mathrm{B}} | \boldsymbol{x}_{\mathrm{A}}, \boldsymbol{x}_{\mathrm{B}}, I)}_{\text{Posterior}} \propto \underbrace{p(\boldsymbol{x}_{\mathrm{A}}, \boldsymbol{x}_{\mathrm{B}} | Q, \boldsymbol{\theta}_{\mathrm{A}}, \boldsymbol{\theta}_{\mathrm{B}}, I)}_{\text{likelihood}} \underbrace{p(Q, \boldsymbol{\theta}_{\mathrm{A}}, \boldsymbol{\theta}_{\mathrm{B}} | I)}_{\text{Prior}}$$

Gaussian process tomography

- Gaussian process prior:

$$p(\boldsymbol{\epsilon}|\boldsymbol{\mu}_{\epsilon 0}, \Sigma_{\epsilon 0}, I) = (2\pi)^{-n/2}|\Sigma_{\epsilon 0}|^{-1/2}$$
$$\times \exp\left[-\frac{1}{2}(\boldsymbol{\epsilon} - \boldsymbol{\mu}_{\epsilon 0})^{\mathrm{t}}\Sigma_{\epsilon 0}^{-1}(\boldsymbol{\epsilon} - \boldsymbol{\mu}_{\epsilon 0})\right],$$

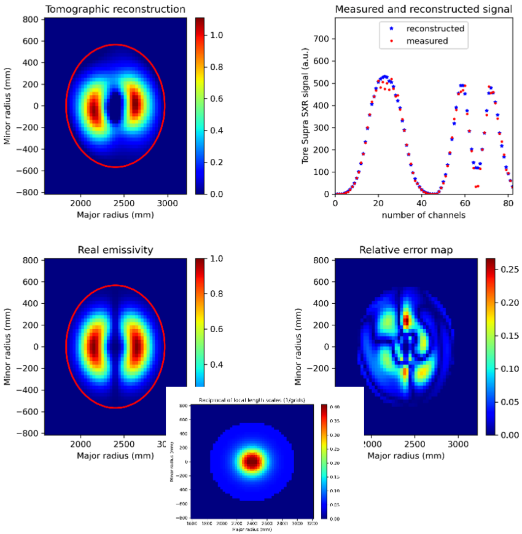


$$\Sigma_{\epsilon 0} = \begin{bmatrix} k(\boldsymbol{r}_1, \boldsymbol{r}_1) & \dots & k(\boldsymbol{r}_1, \boldsymbol{r}_n) \\ \vdots & \ddots & \vdots \\ k(\boldsymbol{r}_n, \boldsymbol{r}_1) & \dots & k(\boldsymbol{r}_n, \boldsymbol{r}_n) \end{bmatrix},$$

$$k(\boldsymbol{r}_i, \boldsymbol{r}_j) = \sigma_{\mathrm{f}}^2 \exp\left[-\frac{1}{2}\left(\frac{\|\boldsymbol{r}_i - \boldsymbol{r}_j\|}{\sigma_{\mathrm{l}}}\right)^2\right]$$

J. Svensson, EFDA-JET PR (11) 24, 2011
D. Li et al., Rev. Sci. Instrum. **84**, 083506, 2013

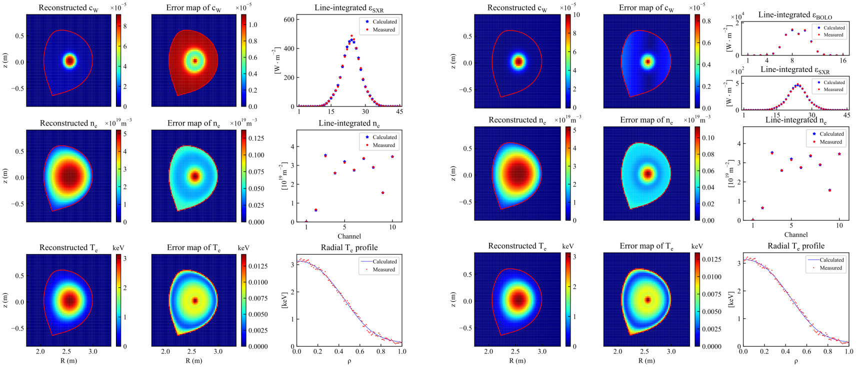
Soft X-ray emissivity reconstruction



T. Wang et al., Rev. Sci. Instrum. **89**, 063505, 2018
H. Wu et al., EPS 2023
H. Wu et al., J. Fus. Energ. **43**, 9, 2024

Integrated tungsten concentration estimation

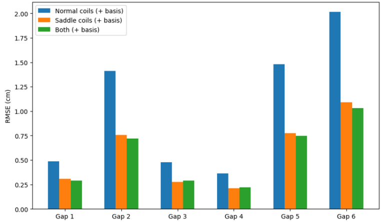
- SXR vs. SXR + bolometry:

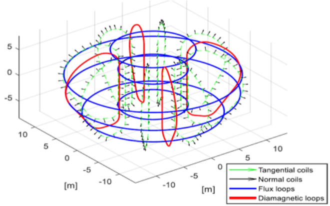


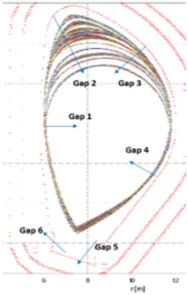
H. Wu et al., J. Fusion Energ. **43**, 9, 2024

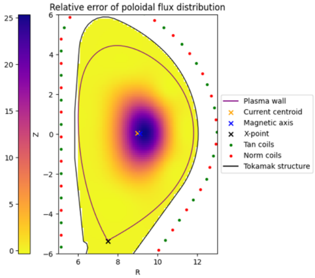
- Real-time performance via neural network emulation

Plasma position in DEMO





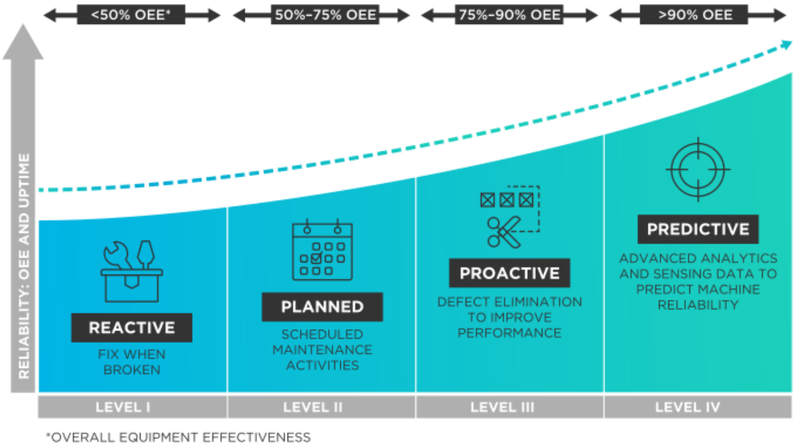




J. De Rycke et al., MaxEnt 2024

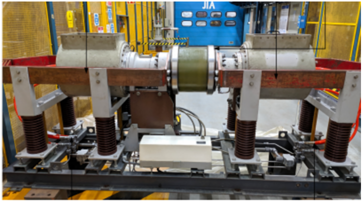
Overview

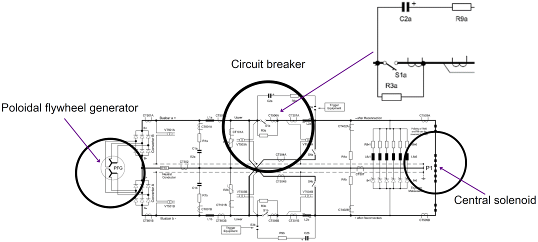
Predictive maintenance

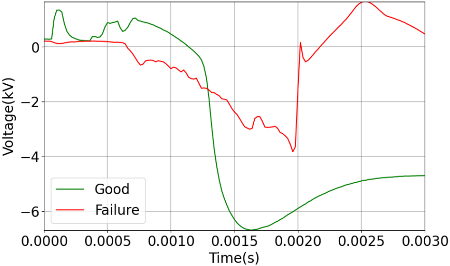


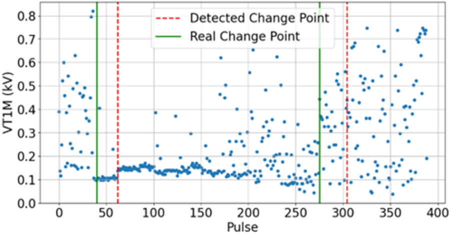
tibco.com

JET Ohmic heating circuit breakers



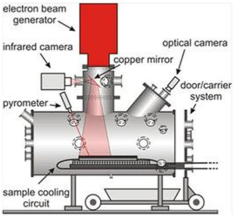




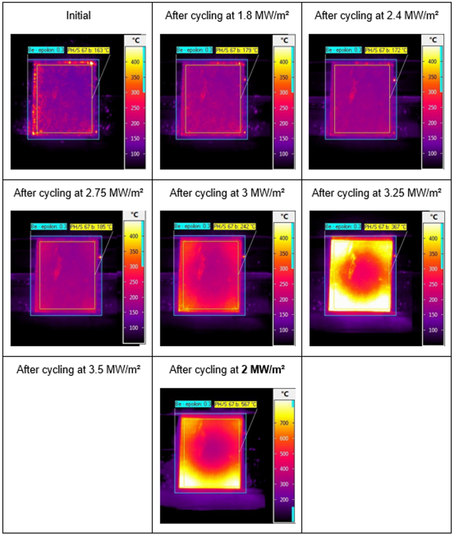


Overheating of beryllium tiles

Electron beam facility JUDITH 2



- max. power 200 kW
- acceleration voltage 30 – 60 kV
- EB diameter ≤ 5 mm FWHM
- loaded area 40 x 40 cm^2



Courtesy of T. Loewenhoff, FZ-Juelich

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FUSION-EP

- European Master of Science in Nuclear Fusion and Engineering Physics
- Two-year joint European master
- 8 Full Partner institutions
- 25 Associate Partners worldwide: CEA-IRFM, CIEMAT, IPP, ITER, SWIP, . . .
- Joint experimentation, Summer Event

With the support of the Erasmus+ Programme of the European Union

Statement on privacy

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CTU Czech Technical University in Prague · Université de Lorraine · Aix*Marseille université Socialement engagée · Universidad Complutense Madrid

https://fusion-ep.eu/

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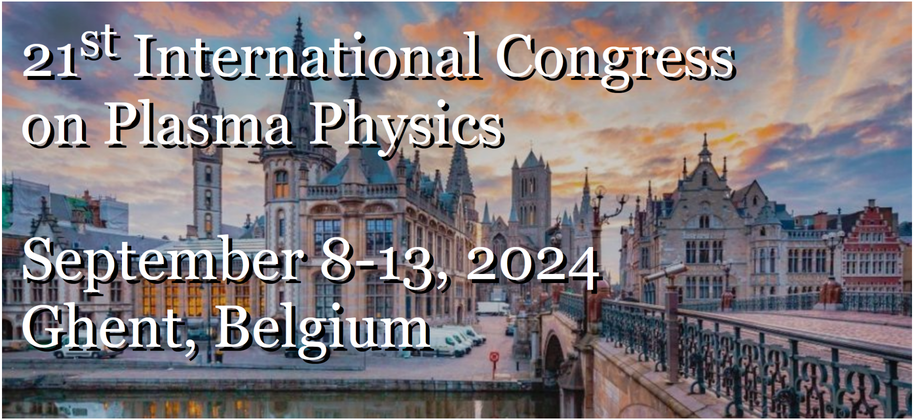

https://icpp2024.ugent.be