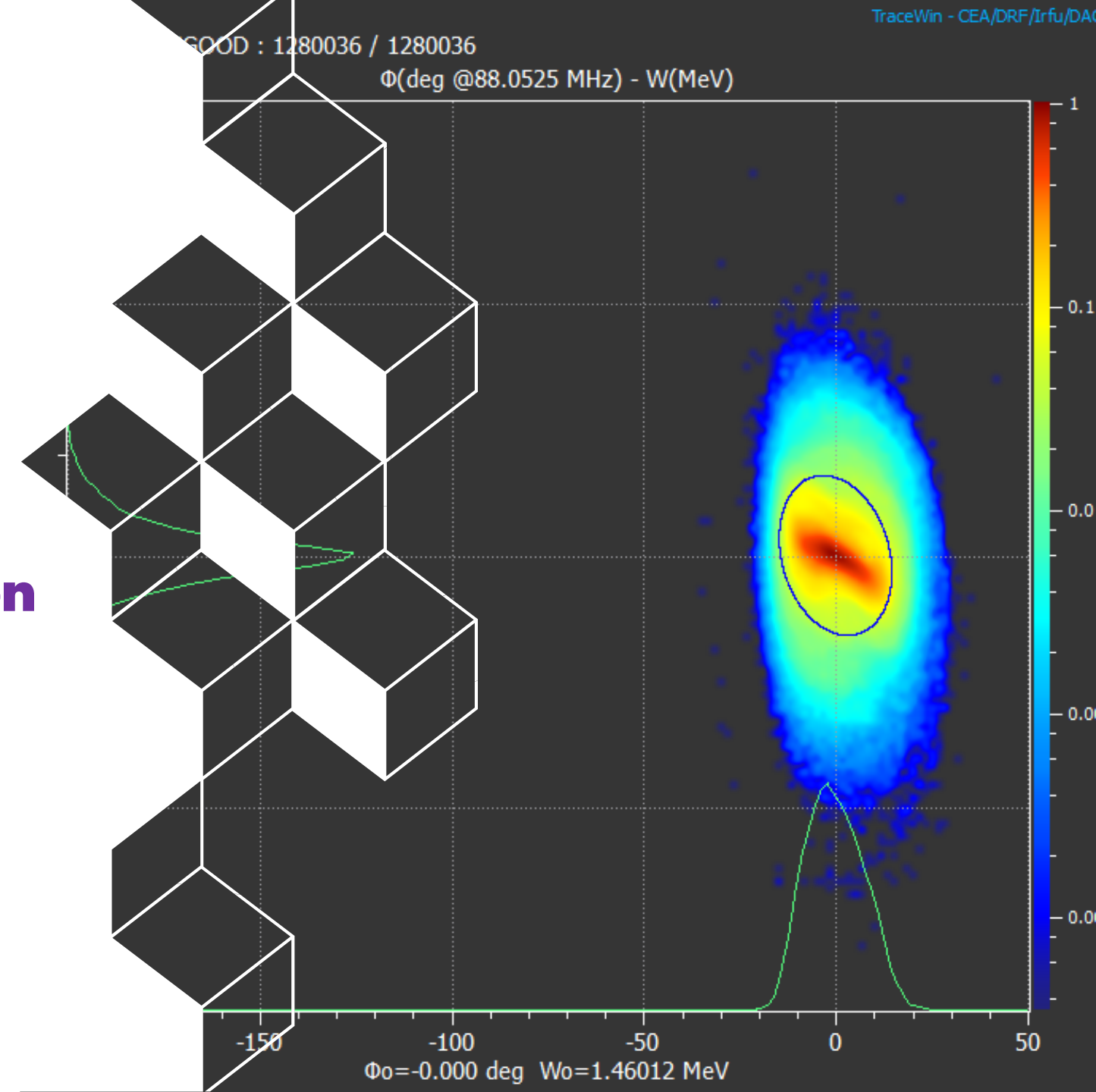
cea irfu

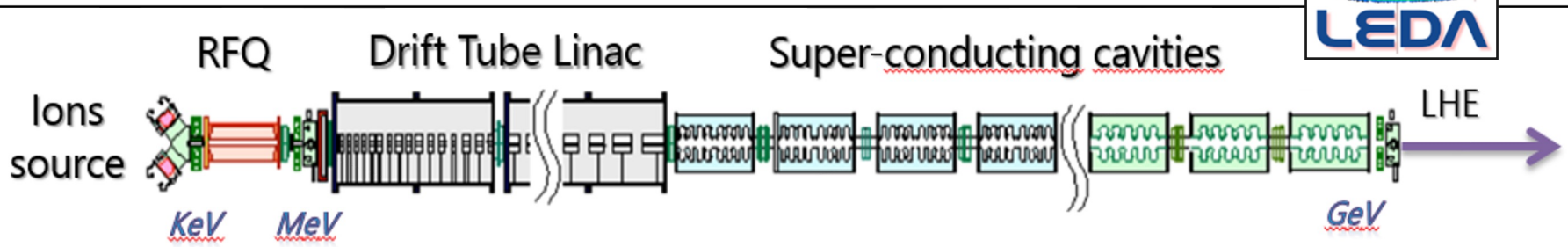
Le code TraceWin, boite à outils pour la conception et l'optimisation d'accélérateurs de particules

Didier Uriot

DACM



Une suite de codes dédiés aux accélérateurs linéaires



Transport codes:

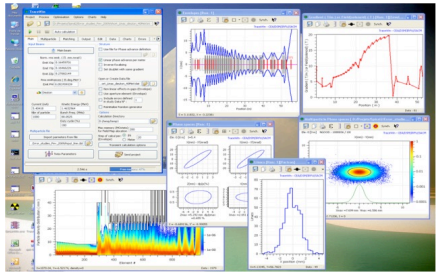
- Toutatis
- TraceWin
- Beta

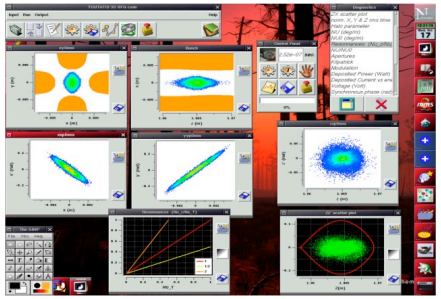
Generator codes:

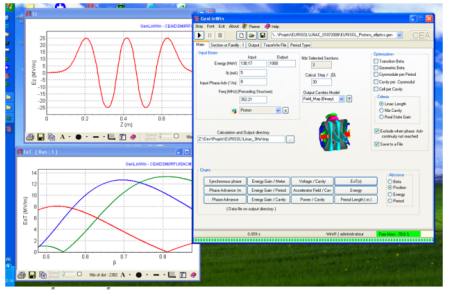
- RFQ_Designer
- GenDTL
- GenLinWin

Visualization:

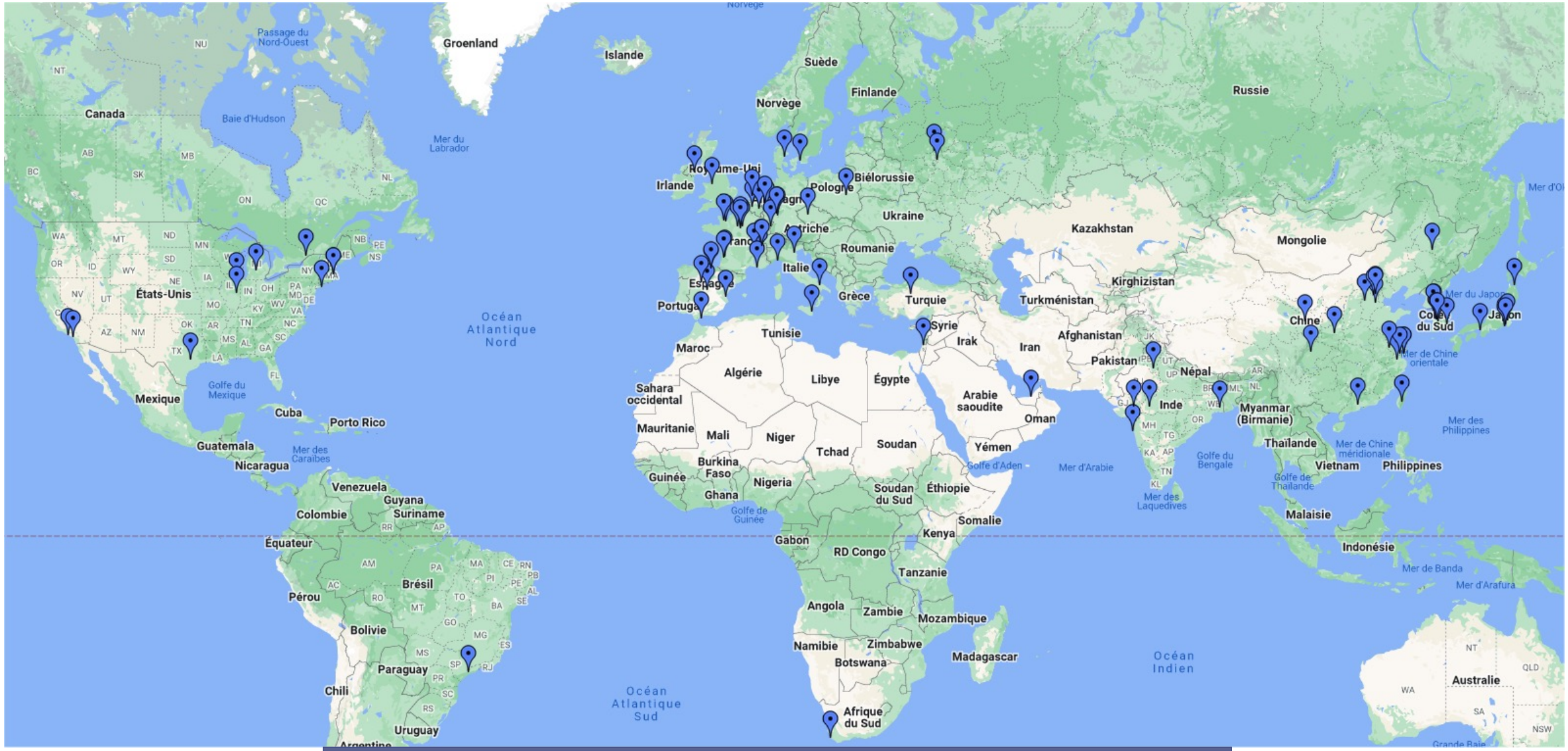
- PlotWin







Une large diffusion internationale



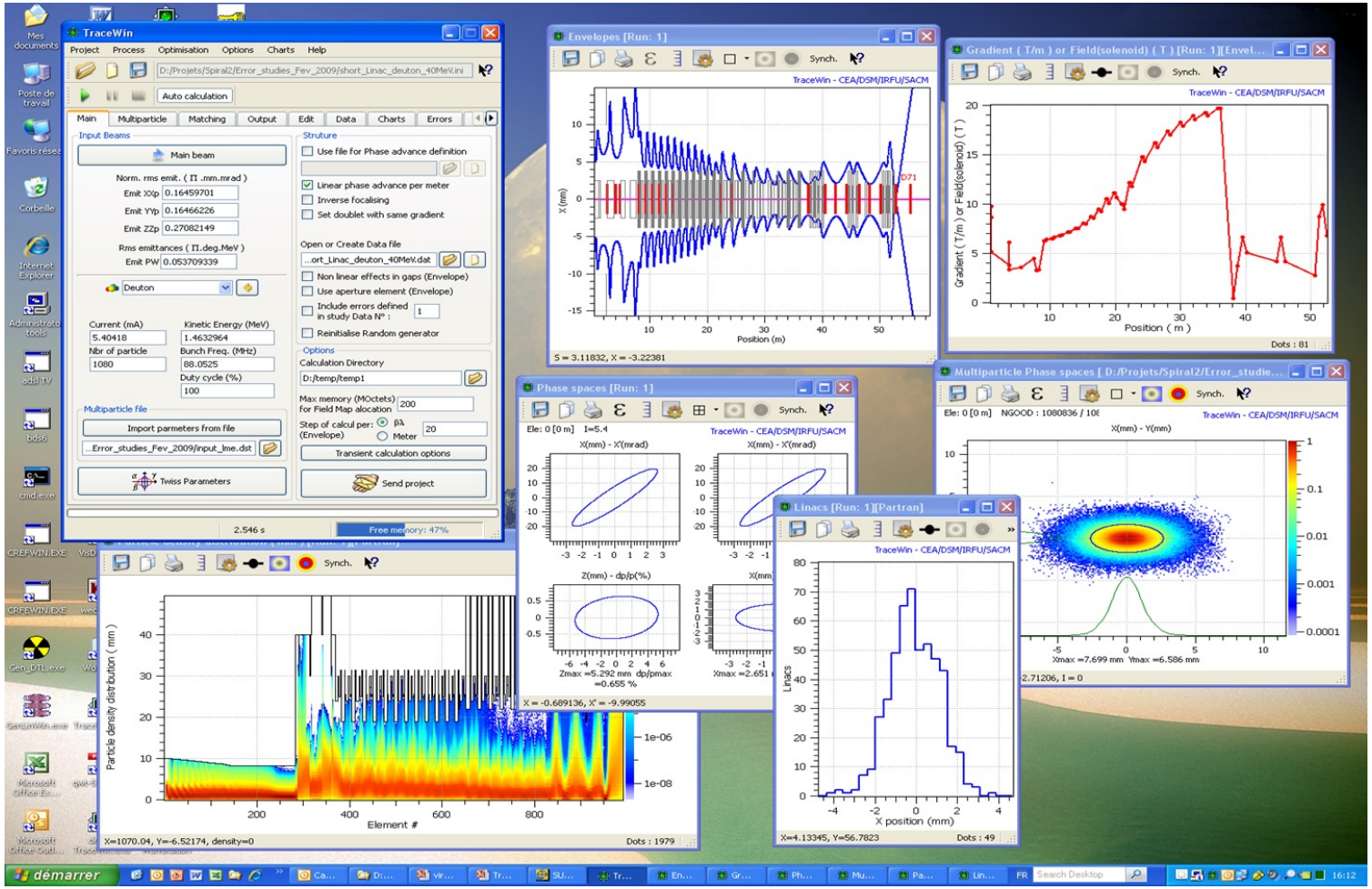
82 laboratoires – 26 sociétés – 27 pays

Les moins

- Source fermées
- Distribué sous licence payante limitée dans le temps
- +100.000 lignes de code
- Mise à jour presque quotidiennes
- Equipe de développeur réduite

Les plus

- Mètre étalon dans la communauté
- Nombreuses validations expérimentales
- Mise à jour presque quotidiennes
- Multi OS (Windows, Linux, Mac)
- Stand-alone,
- GUI



Pourquoi TraceWin ?

- Initialement dédié au accélérateur linéaire de haute intensité
- Objectif de productivité et d'indépendance
- A partir d'un cahier des charges, les attendues sont:
  - Les types et positions des éléments constituant l'accélérateur,
  - Les amplitudes des amplificateurs et alimentations,
  - Les phases des différents éléments accélérateurs (RF),
  - Les tolérances et précisions,
  - La stabilité du système,
  - Les schémas de correction,
  - Les probabilités de perte faisceau.

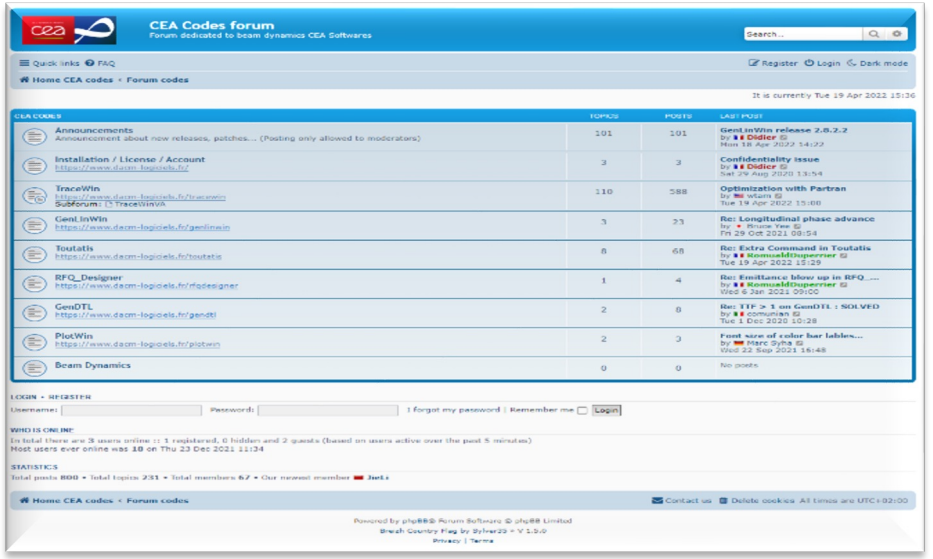
TraceWin permet de répondre à toutes ces questions de manière progressive, via des modèles de plus en plus complexe et proche de la réalité.
L'ensemble des données est aisément visualisable et publiable

The main features and highlights are:

- A wide range elements including RFQ with Toutatis module,
- Own elements
- 1D, 2D, 3D static and dynamic fields map (with superposition capability),
- Envelope and macro-particle tracking simulations,
- Start-to-end simulations from source to target,
- Transport of two beams in the same structure,
- Gas stripping and scattering analysis,
- 2D or 3D space-charge
- Automatic transverse and longitudinal beam tuning,
- Correction procedure based on diagnostics,
- Static and dynamic error simulations for all elements,
- Simulations with large number of particles for large scale computations (Monte Carlo) based on a client/server architecture,
- Statistic analysis including beam loss location,
- Tool to study RF transient,
- GUI and various help tools,
- Windows/Linux/MaCOS versions,
- Reference code for ESS, IFMIF, LINAC4, SPIRAL2, MYRRHA, SARAF, DONES…
- Successful comparison with experiments,
- Virtual accelerator.

https://www.dacm-logiciels.fr/

https://dacm-codes.fr/forum/



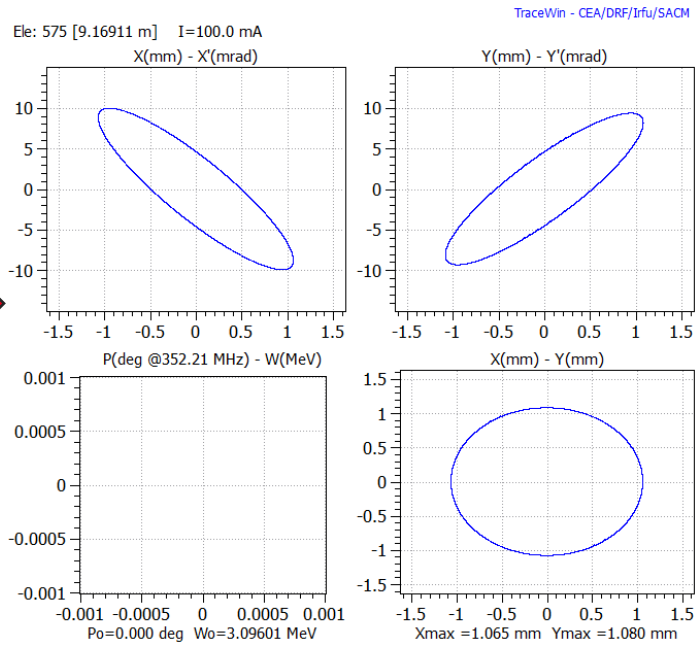
Linear and tracking simulations

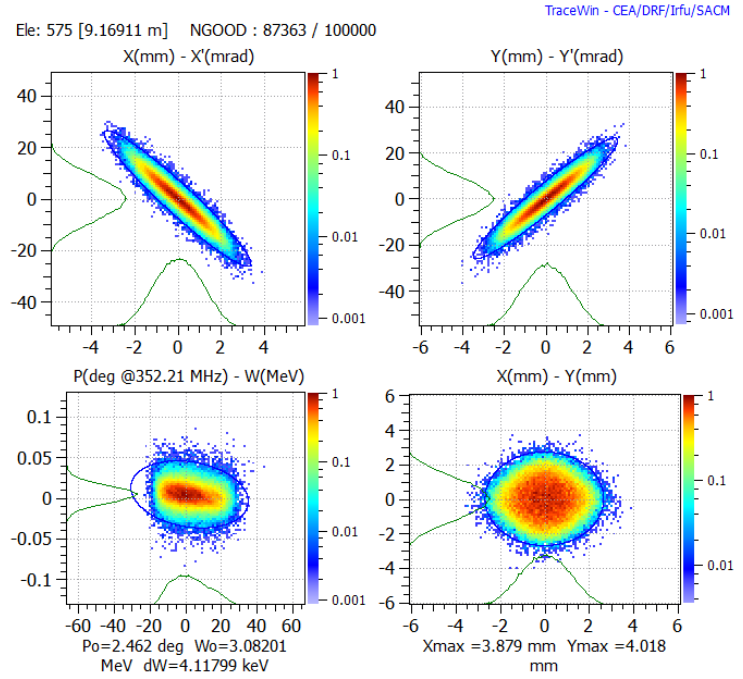
TraceWin code combines the two most common transport techniques used in accelerators community:

- Transport of statistical properties of the beam: the beam is modeled by a (6x6) σ matrix (Beam matrix) corresponding to its 2nd order momentums (dimensions and quadratic coupling means). The transport of this matrix can be carried out using the transfer matrices of the linear or linearized elements. The space charge is linearized and calculation times are very short. (**Matrix / Envelope transport**)

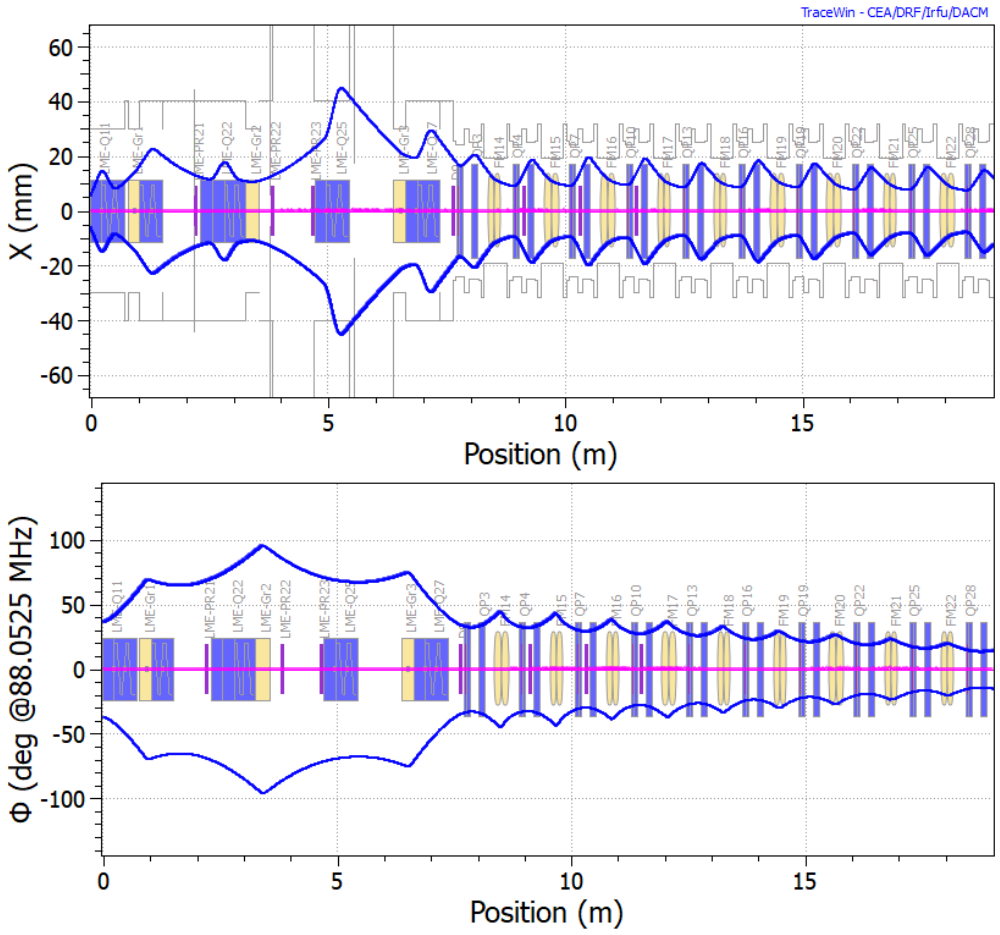
- Transport of a sample of macro-particles: the representation is more accurate and the models used to describe the various elements of the structure are analytic and/or numeric and often non-linear. The space-charge is treated by a PIC method (Particles In Cells) and the calculation time are mainly related to the number of macro-particles used. Particle interactions between them and their environment such as residual gas, can be also included. (**Multiparticle / Tracking transport / Partran**)

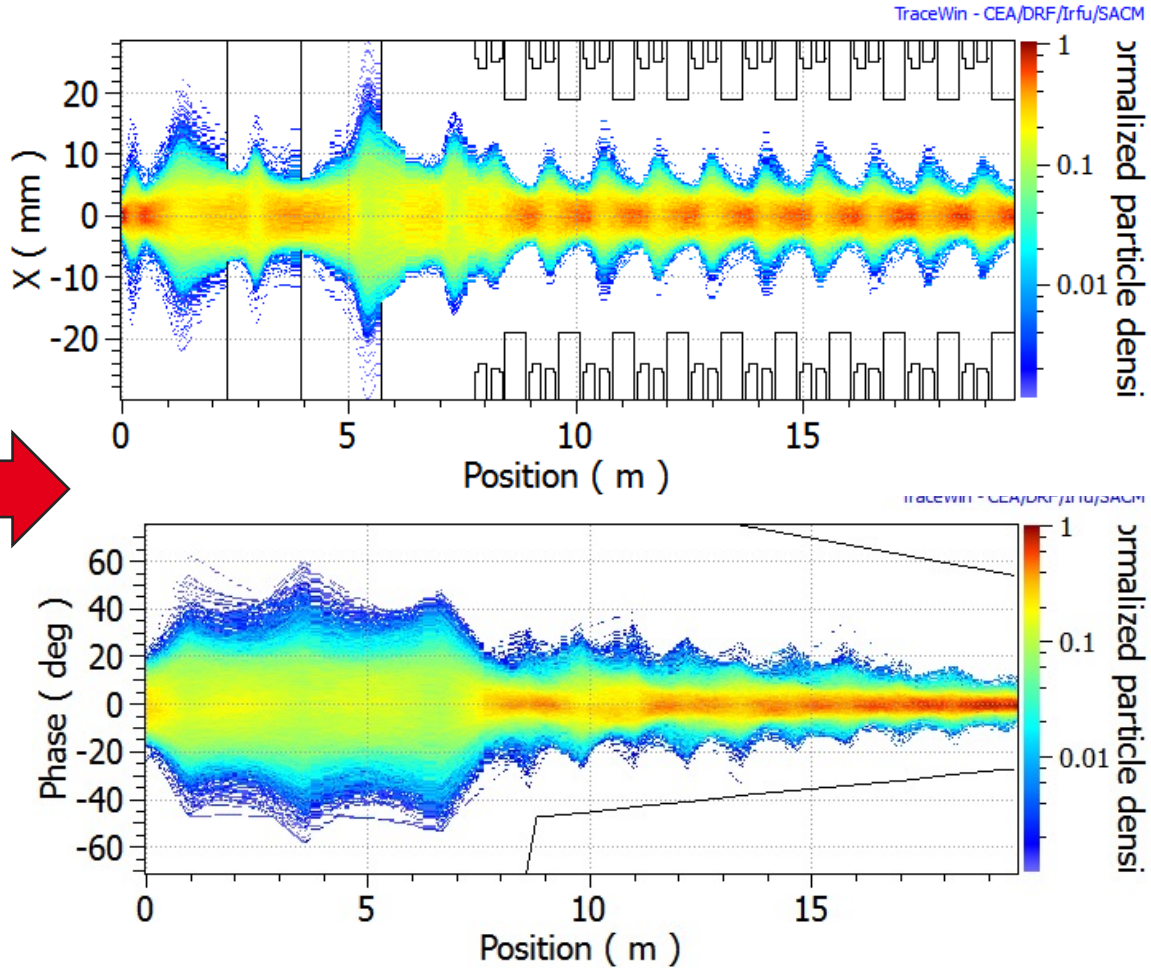
$$\sigma_{xx} = \begin{bmatrix} \beta_x \varepsilon_x & -\alpha_x \varepsilon_x \\ -\alpha_x \varepsilon_x & \gamma_x \varepsilon_x \end{bmatrix}$$





Linear and tracking simulations





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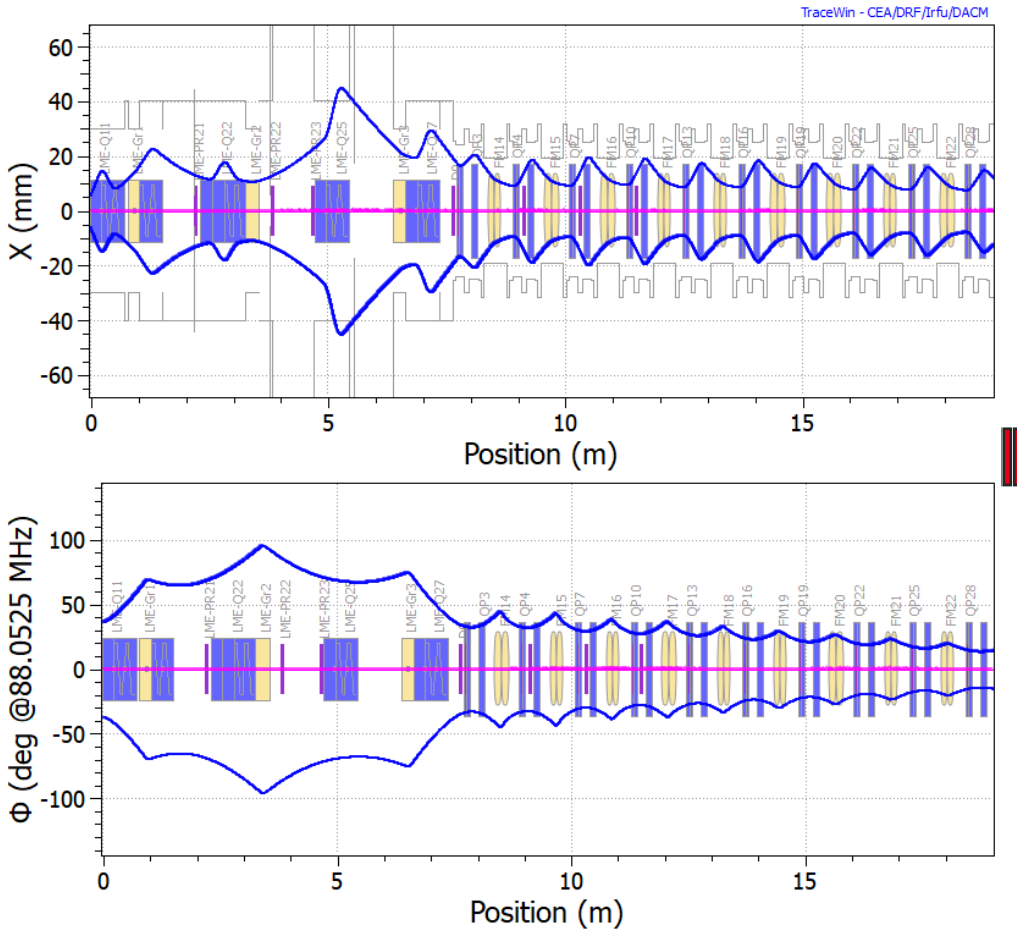
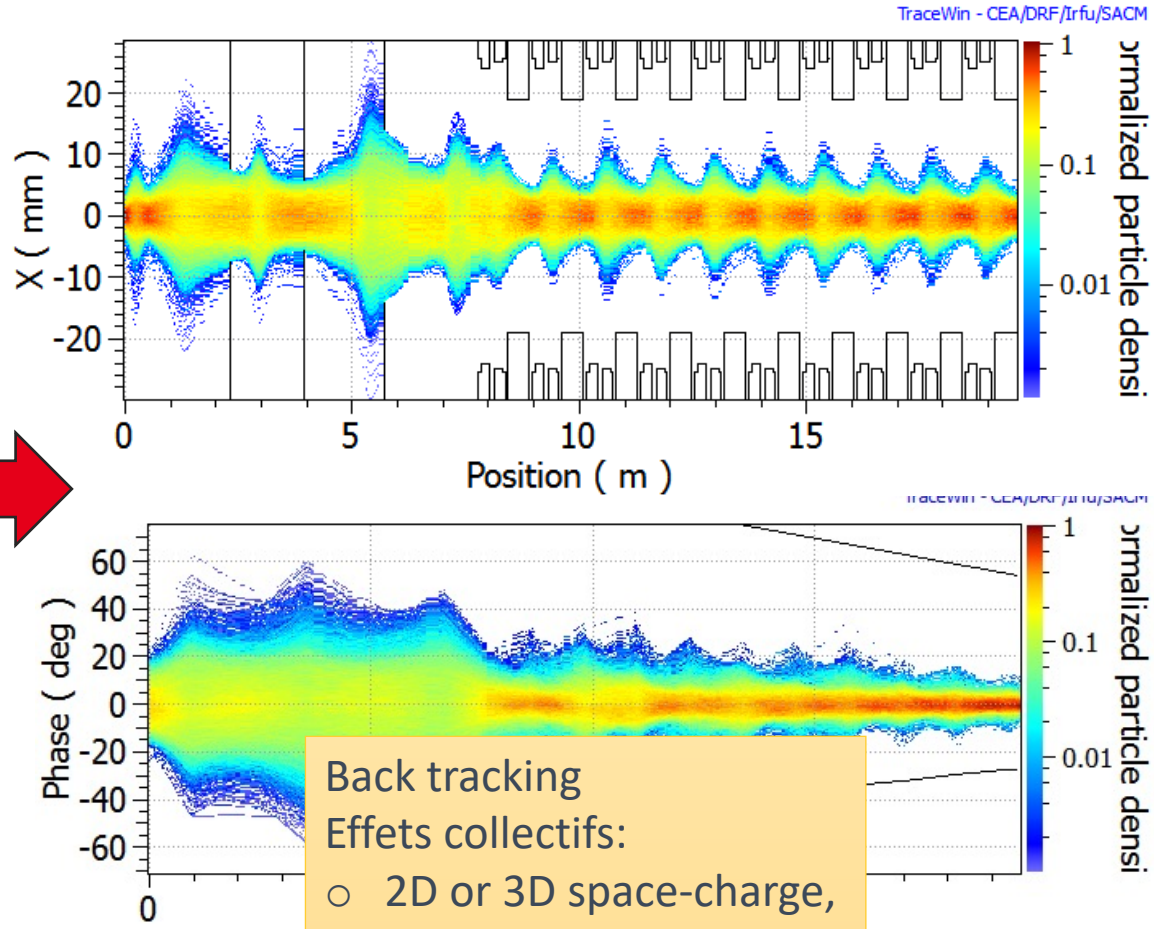


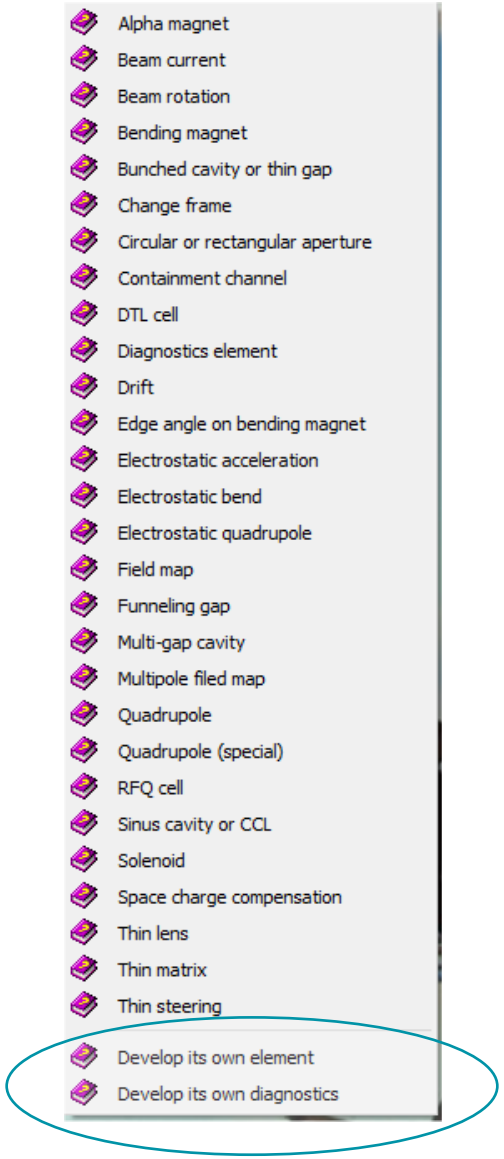


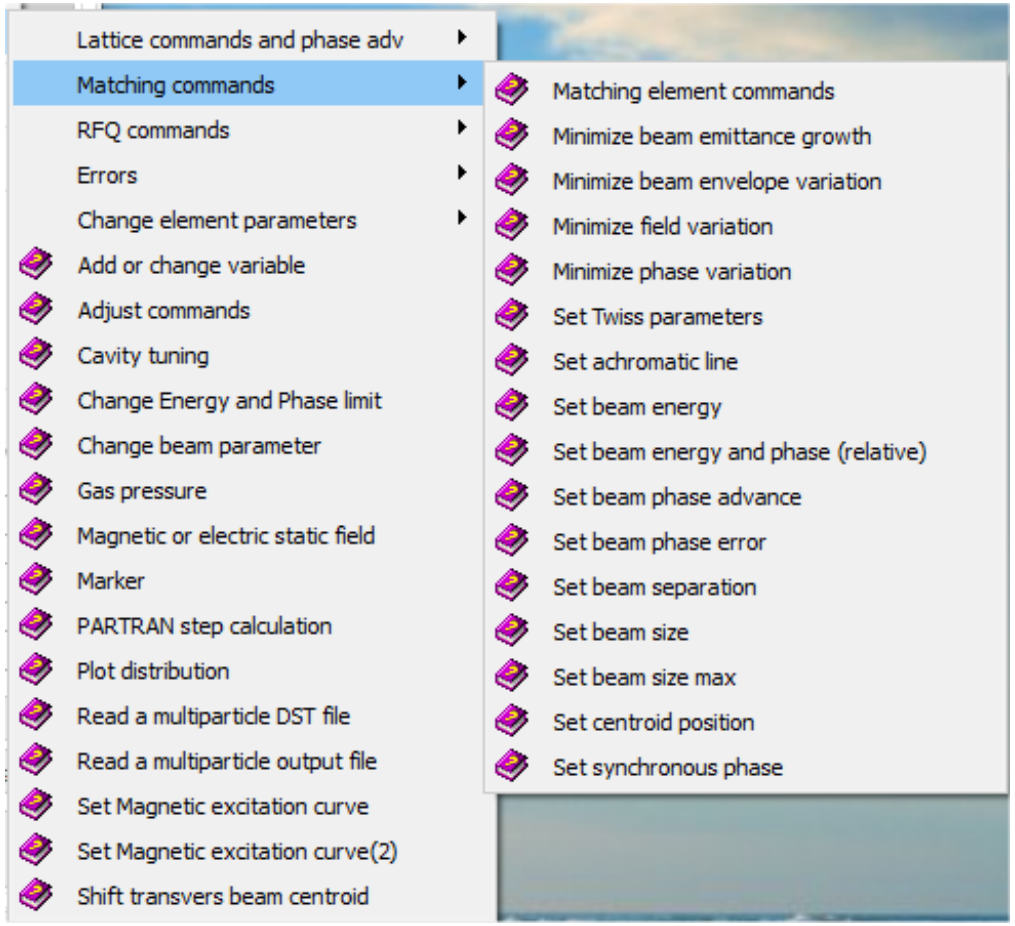
Back tracking

Effets collectifs:

- 2D or 3D space-charge,
- Gas stripping,
- Gas scattering,
- Magnetic stripping,
- Intra-beam stripping,
- Synchrotron radiation.

Description de la machine





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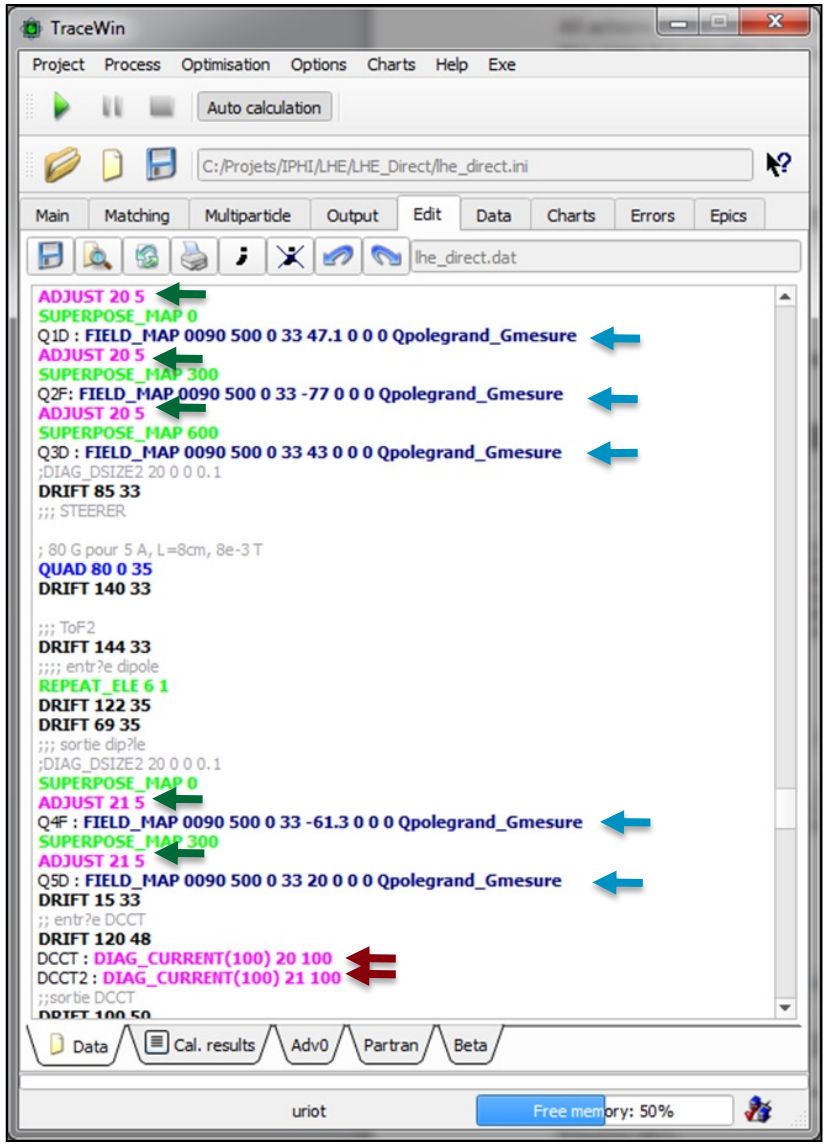
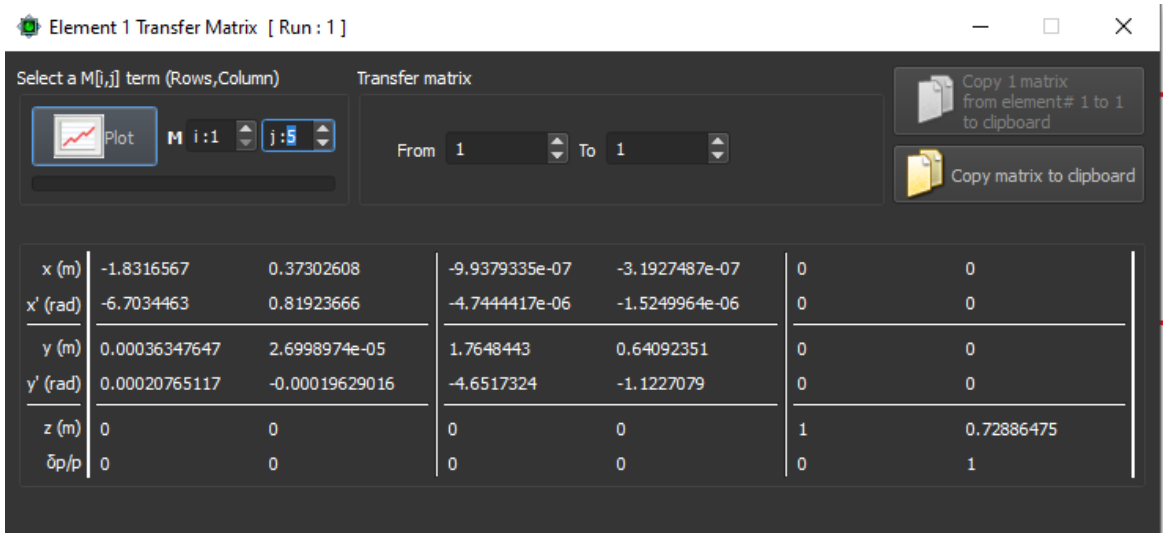


Définition de la machine dans TraceWin:

- Les éléments magnétique et cavités.
- Les diagnostics
- Les procédures ou scripts de réglage

$$R_{xx} = \begin{bmatrix} \cos(k_x \Delta s) & \frac{\sin(k_x \Delta s)}{k_x} \\ -k_x \sin(k_x \Delta s) & \cos(k_x \Delta s) \end{bmatrix} \quad R_{zz} = \begin{bmatrix} 1 & \frac{\Delta s}{\gamma^2} \\ 0 & 1 \end{bmatrix}$$



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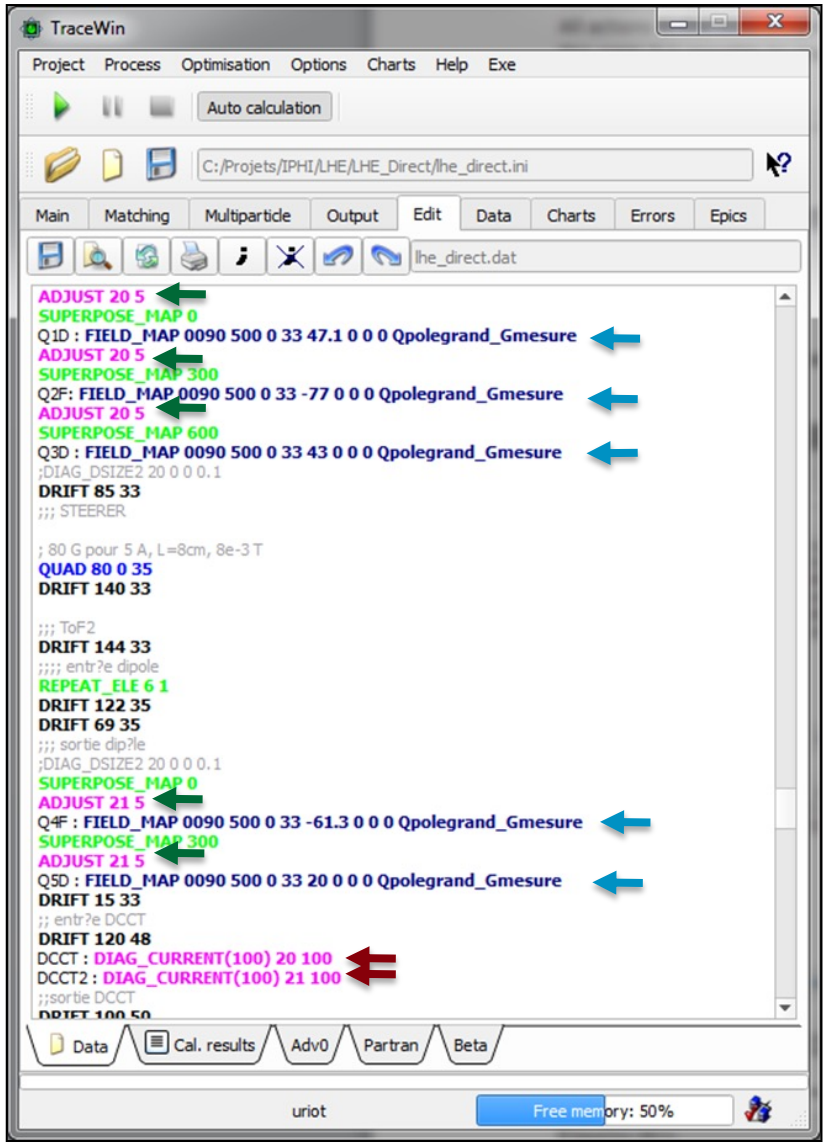

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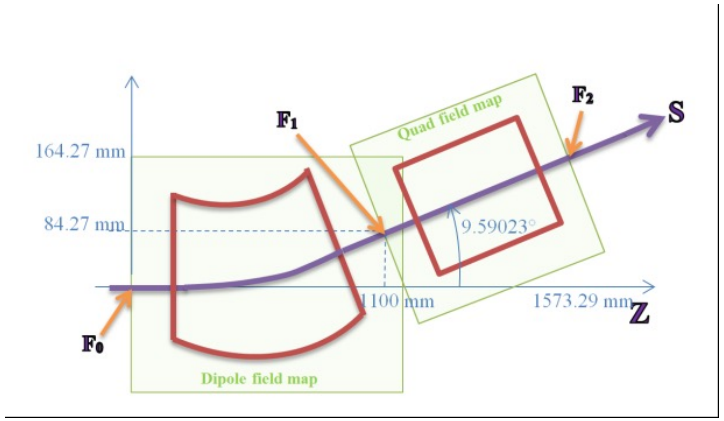
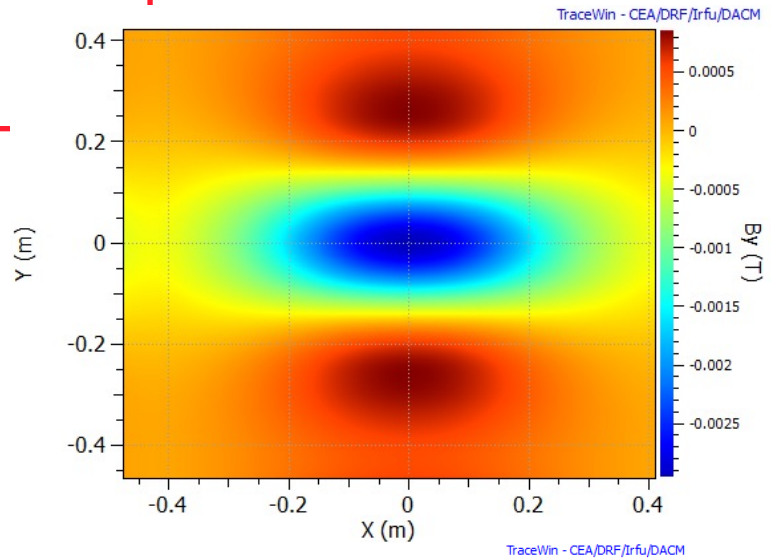
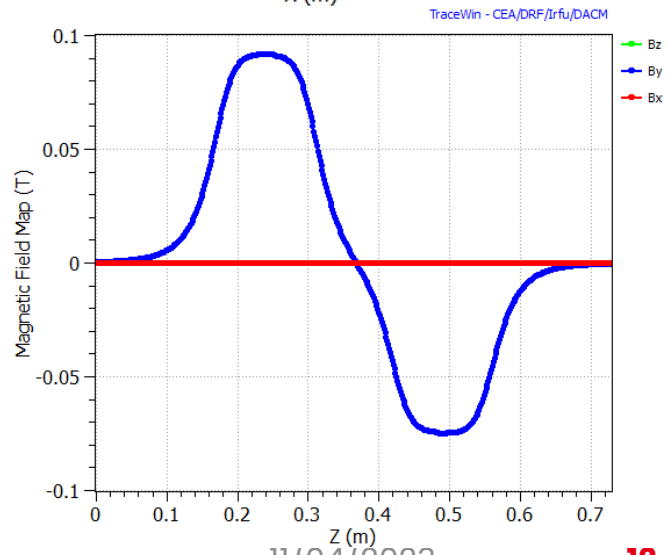
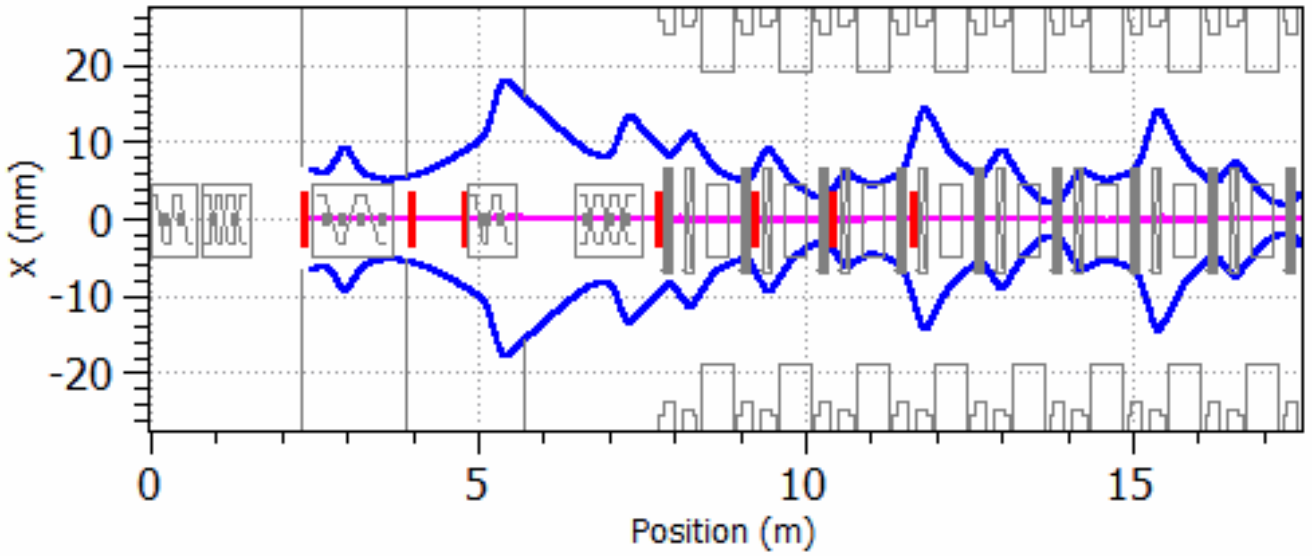


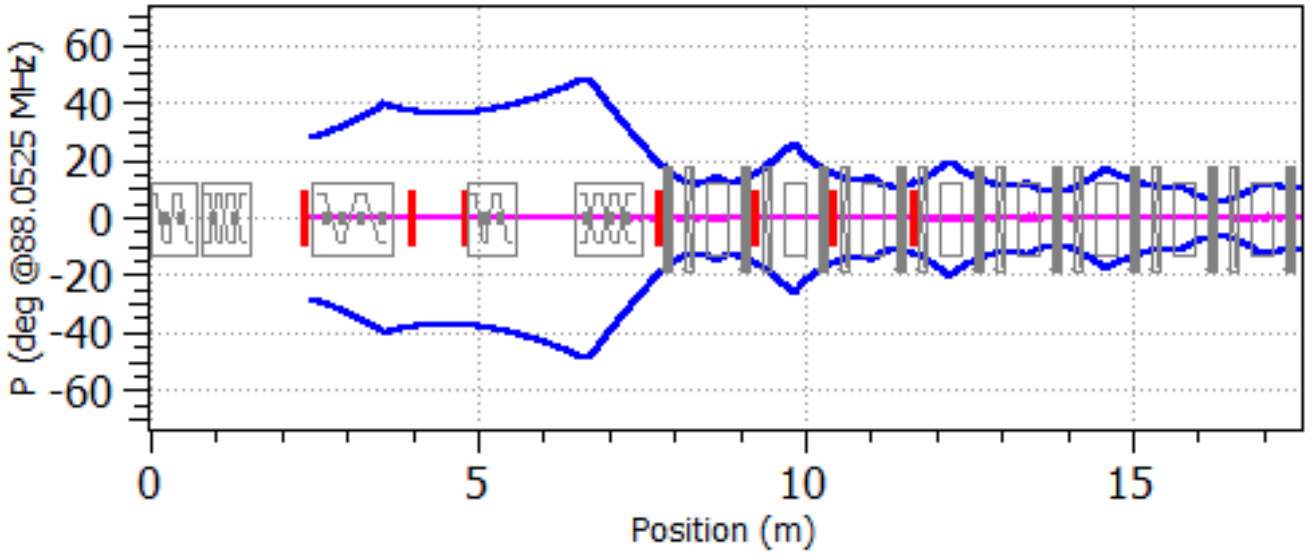
1D, 2D, 3D static and dynamic fields map (with superposition capability),

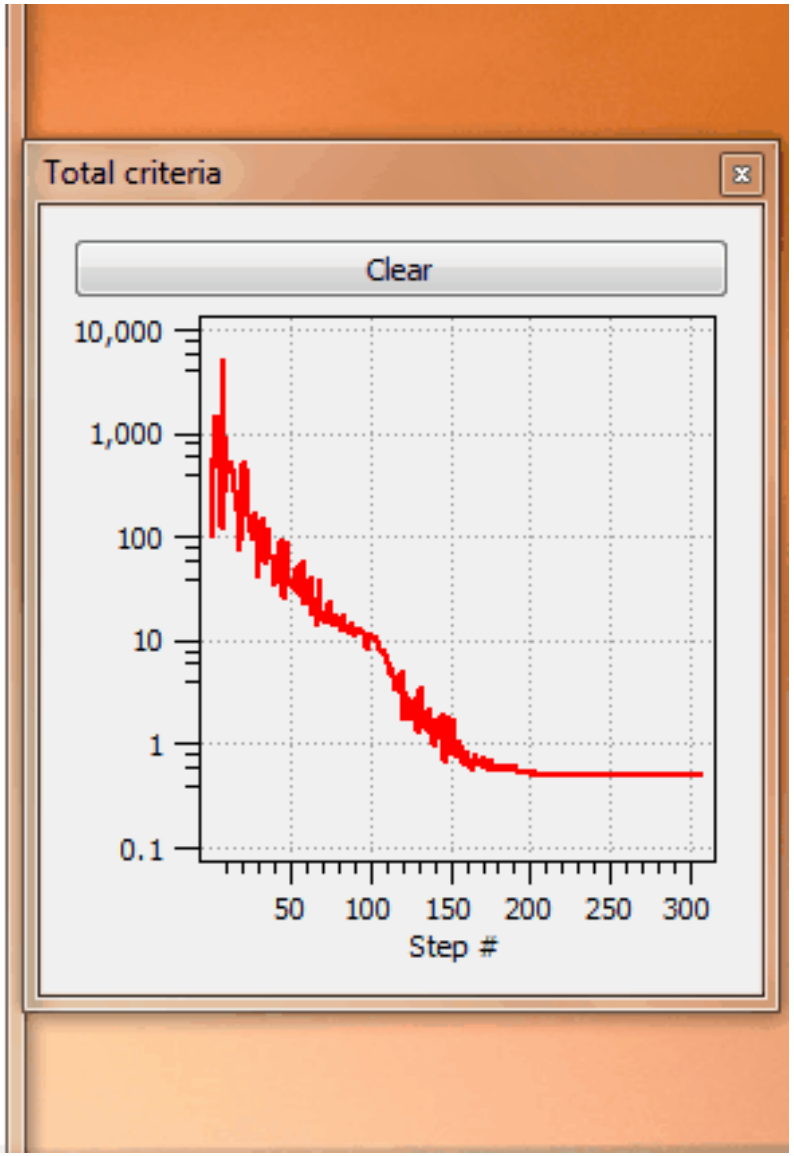




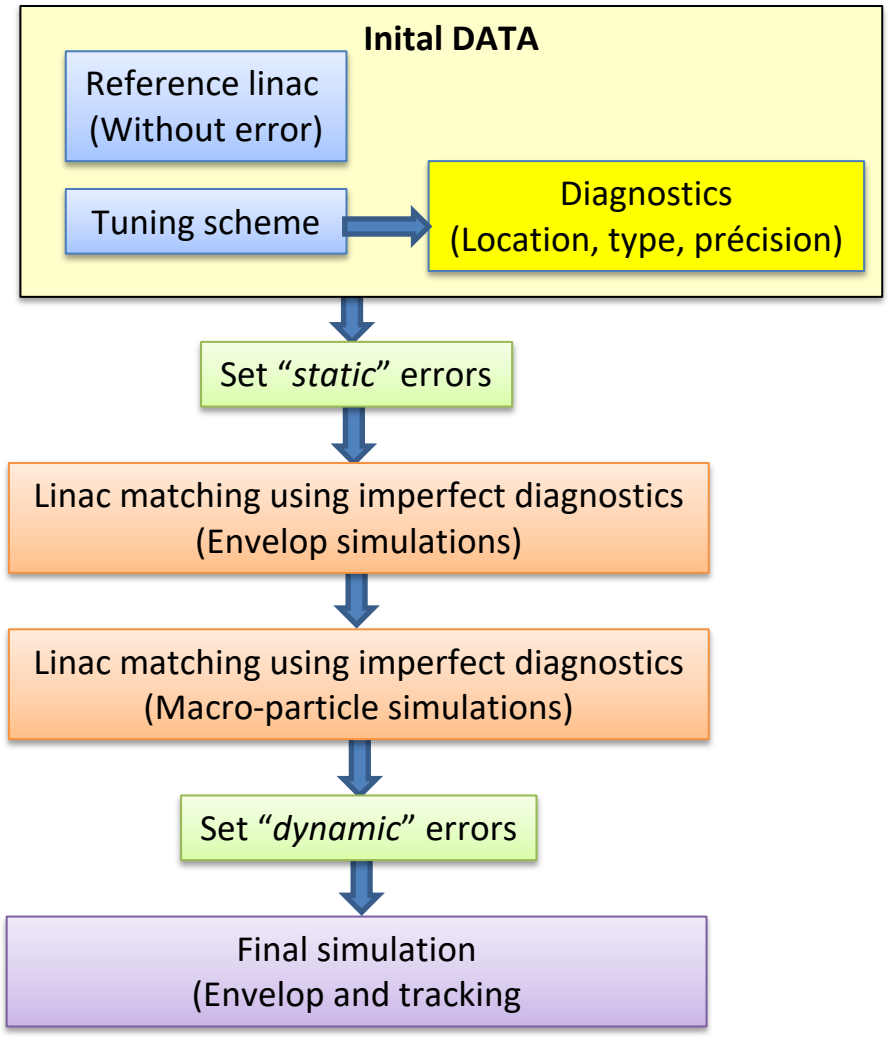
Réglage de la machine



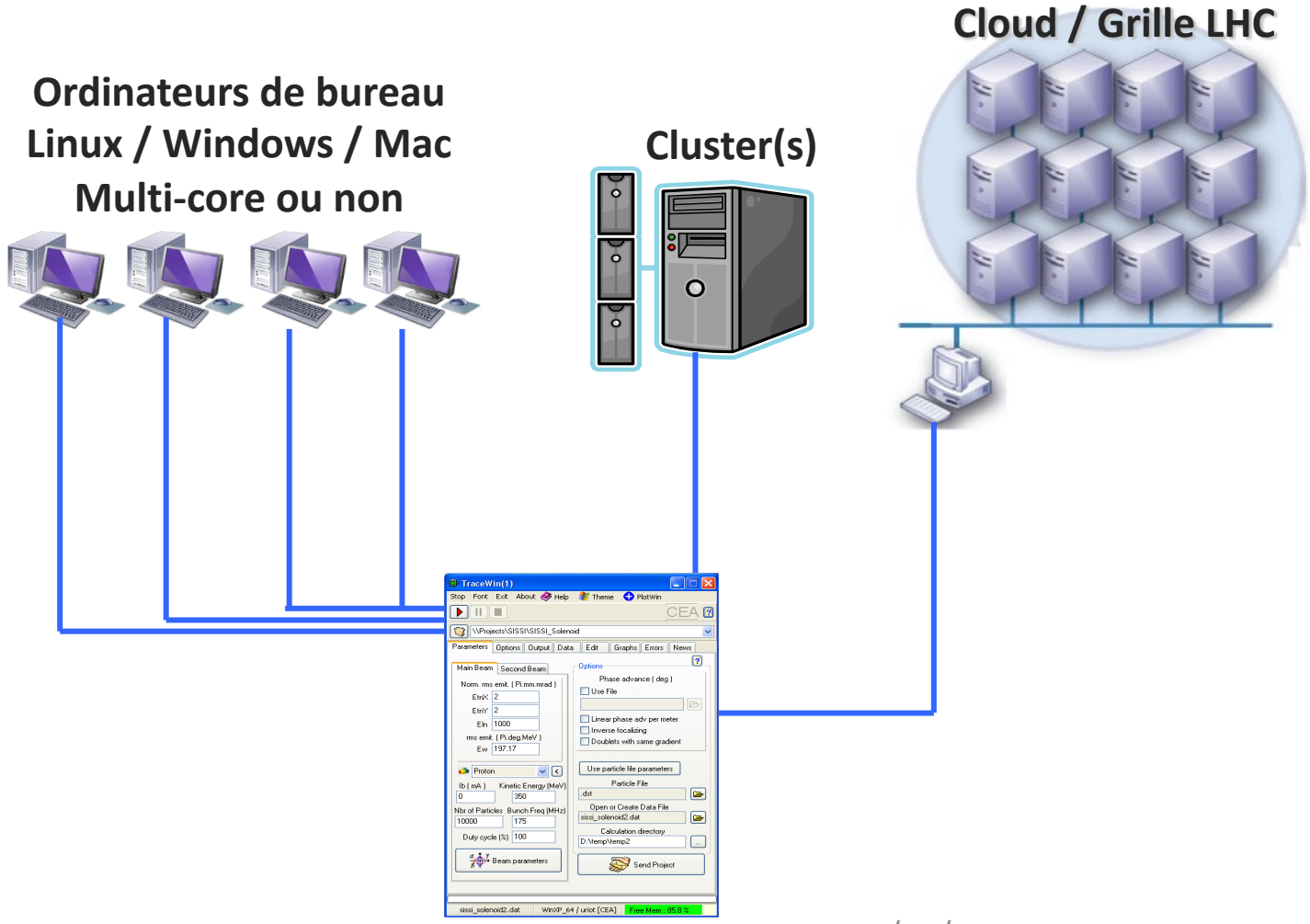




Etude statistique

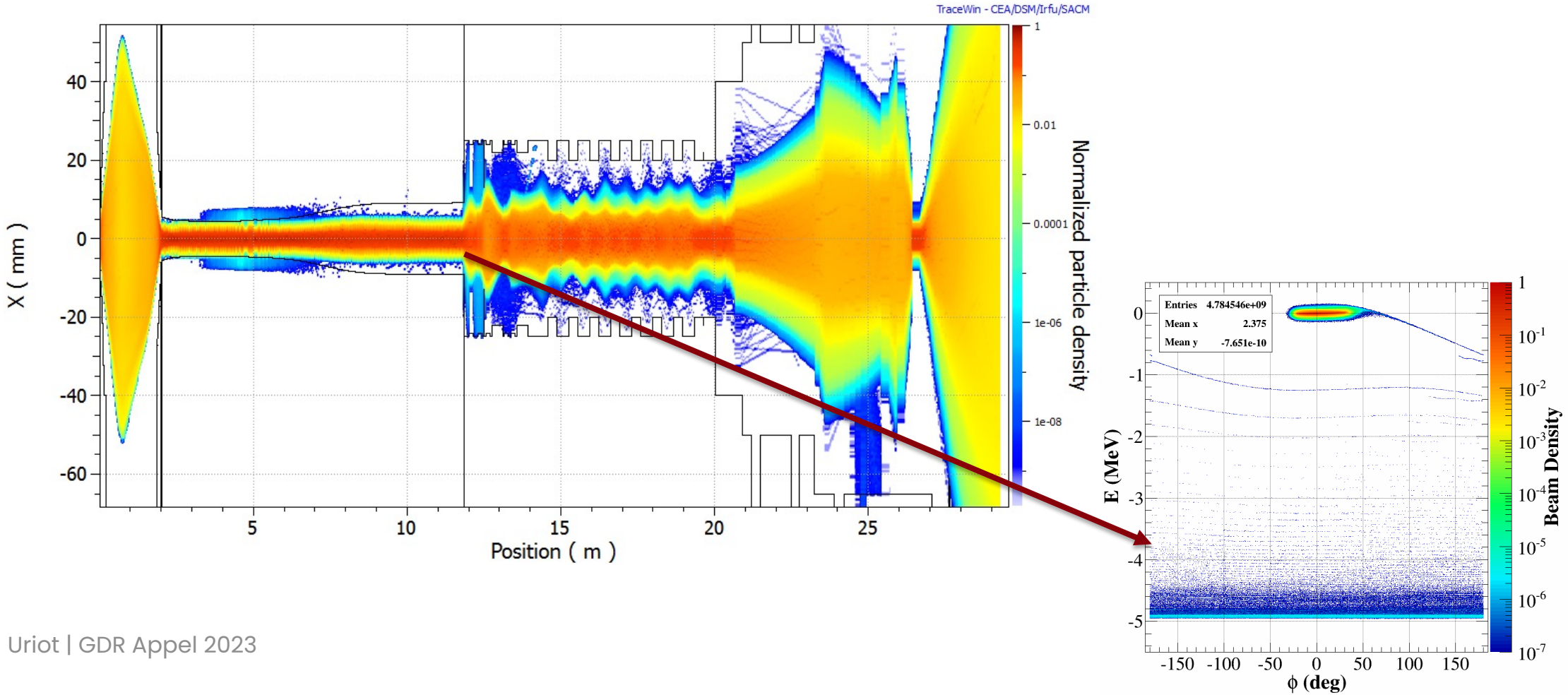


- Simulations with large number of particles for large scale computations (Monte Carlo) based on a client/server architecture,
- Statistic analysis including beam loss location,



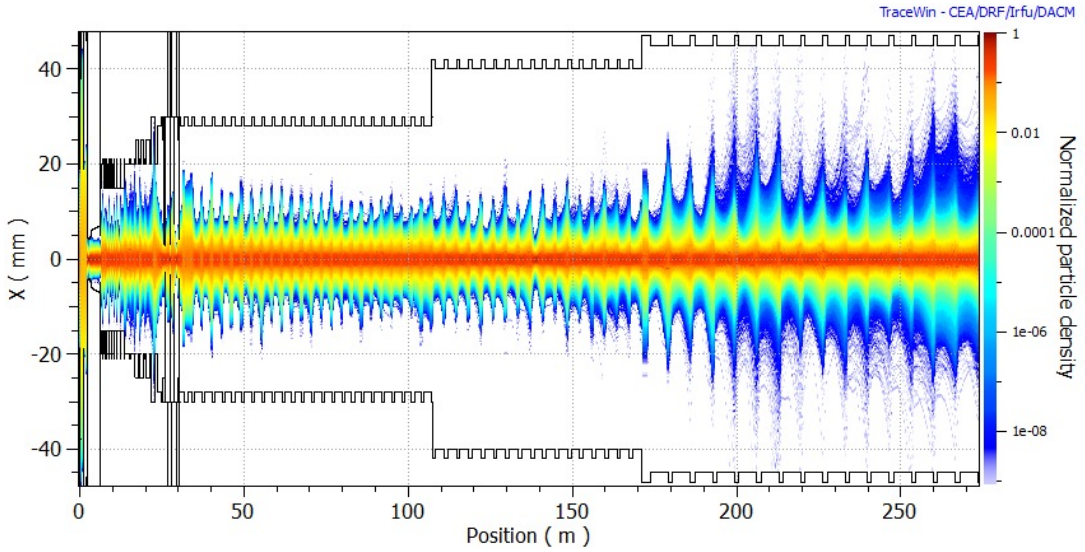
Etude statistique, EVEDA exemple

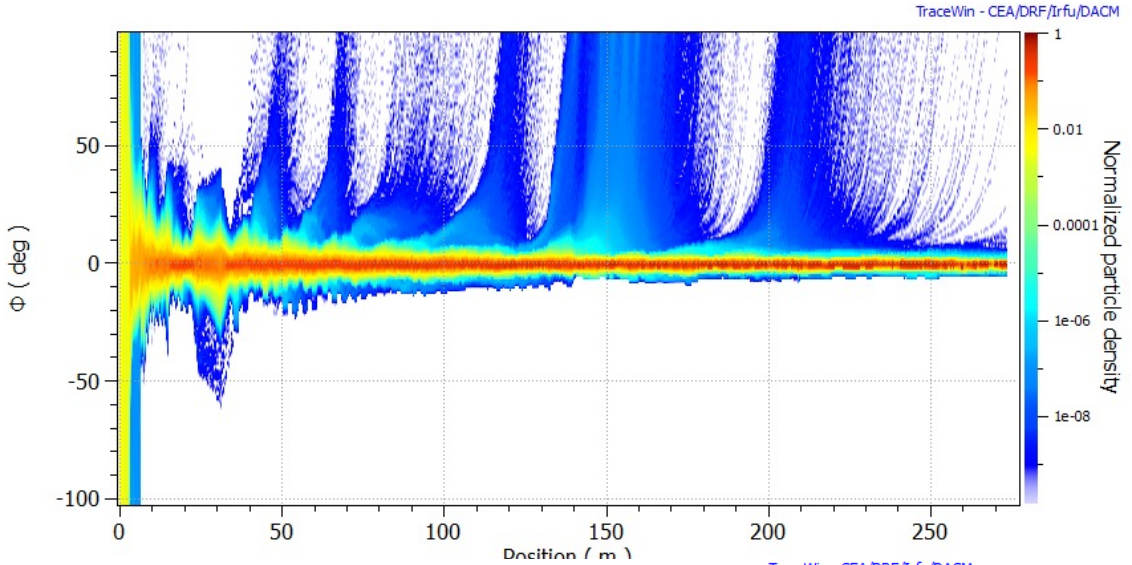
- Simulation massive d'EVADA de la source à la cible (objectif: études du Halo & pertes), en incluant le nombre réel de particules dans le bunch (**4.7 10^9** particules),
- L'ensemble de la machine est représenté en cartes de champ 3D,
- 150 cœurs, 25 jours, 38 téraoctets.

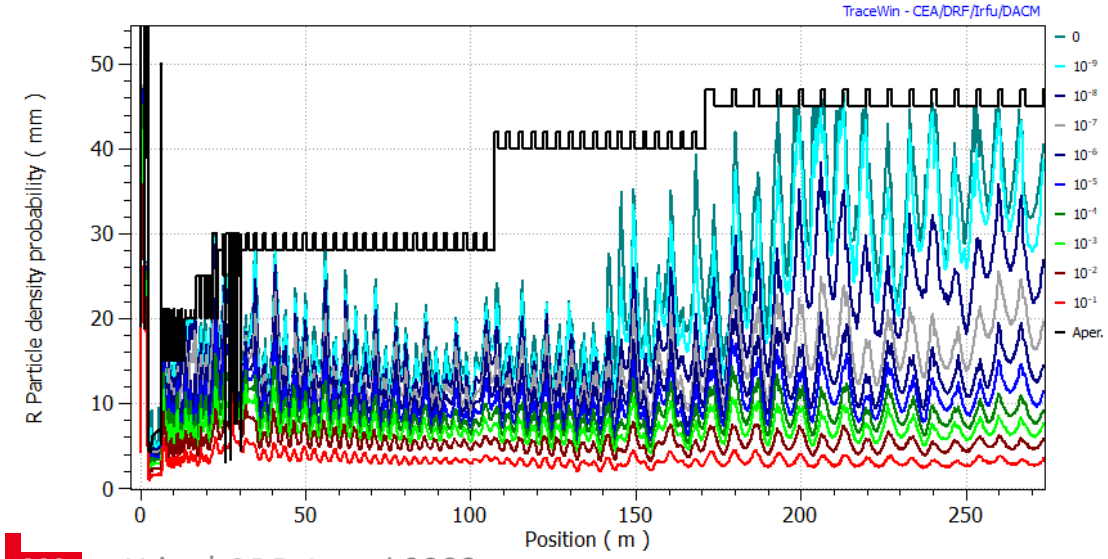


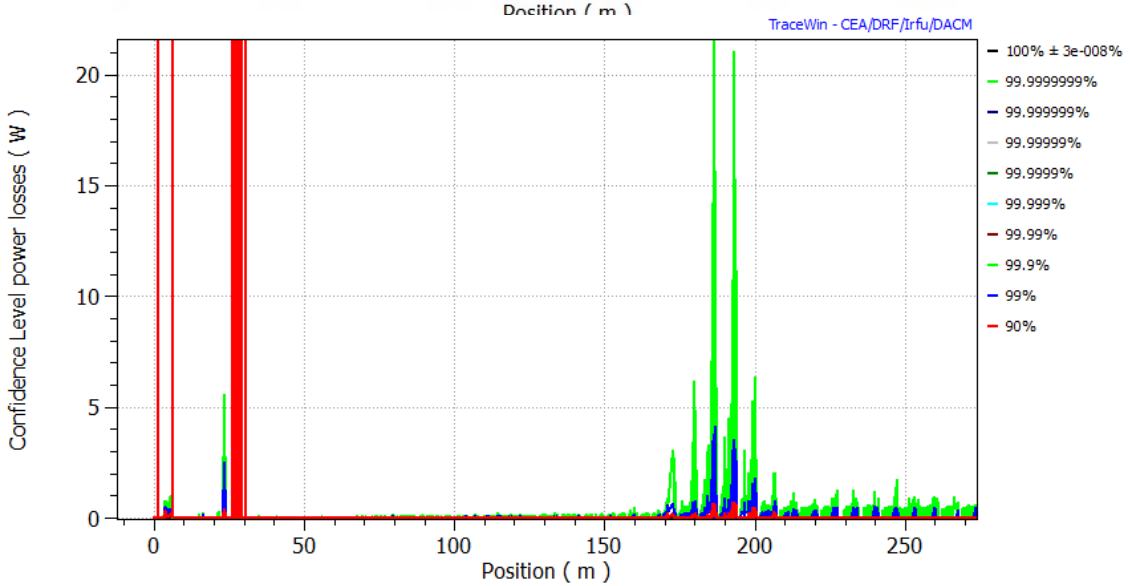
Etude statistique, MYRRHA exemple

- Simulation massive de MYRRHA (1000 x 2 10^6 particules)

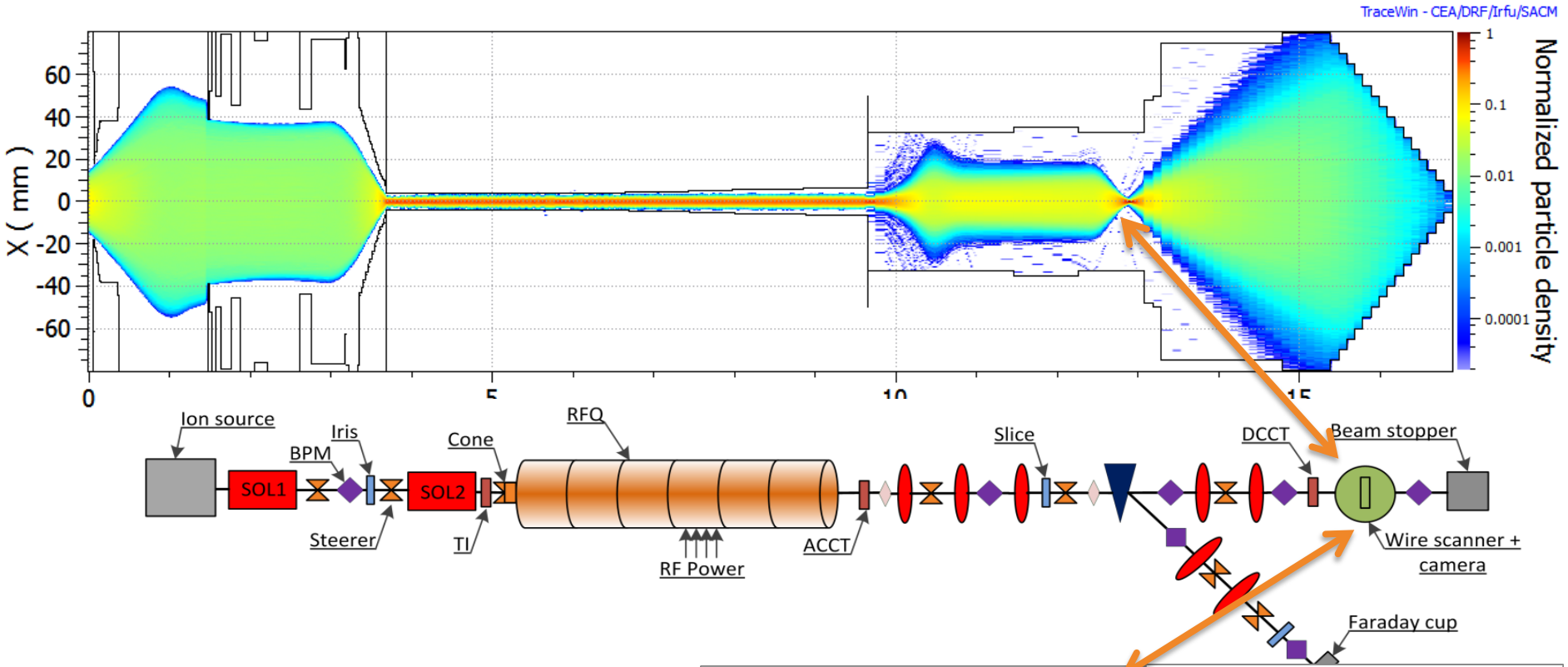


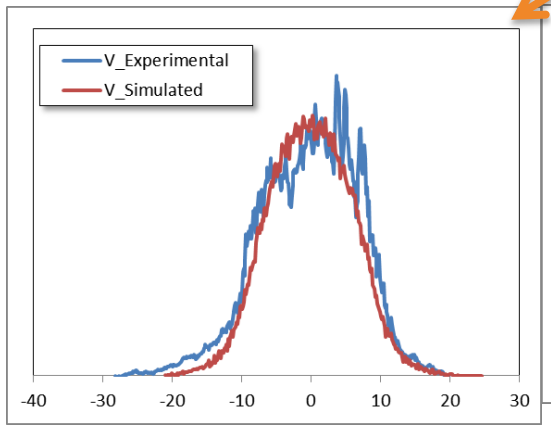


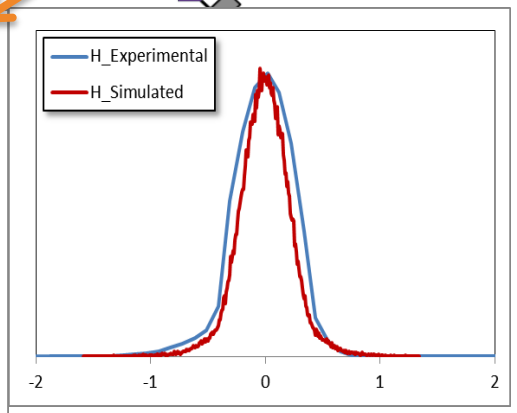




Validation expérimental, IPHI (70 mA)



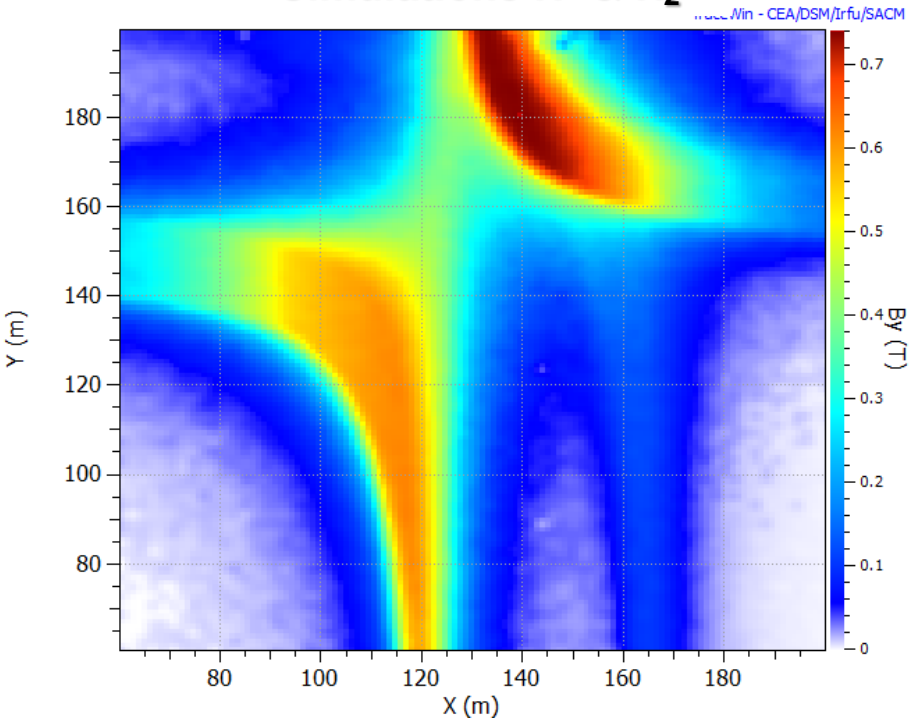




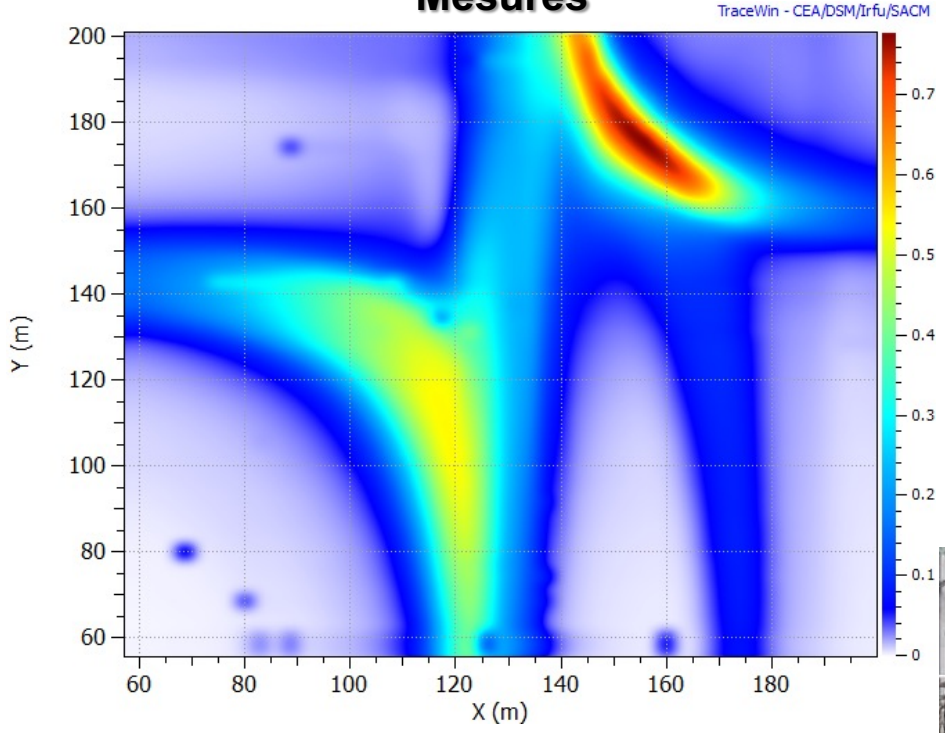
Transmission	Simulated	Experimental
RFQ	98 %	94 %
LHE	100 %	92 %

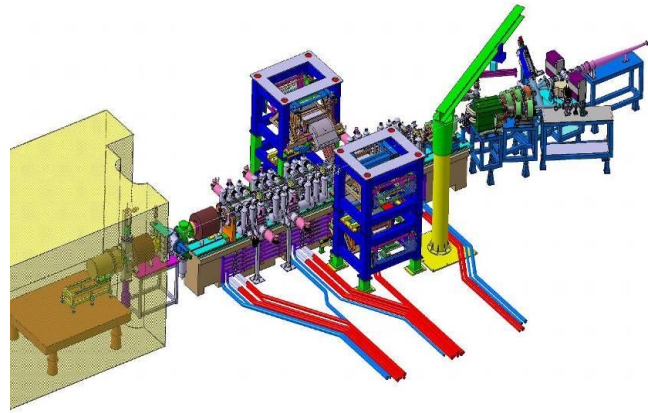
Validation expérimental, IPHI (70 mA)

Simulations H^+ & H_2^+



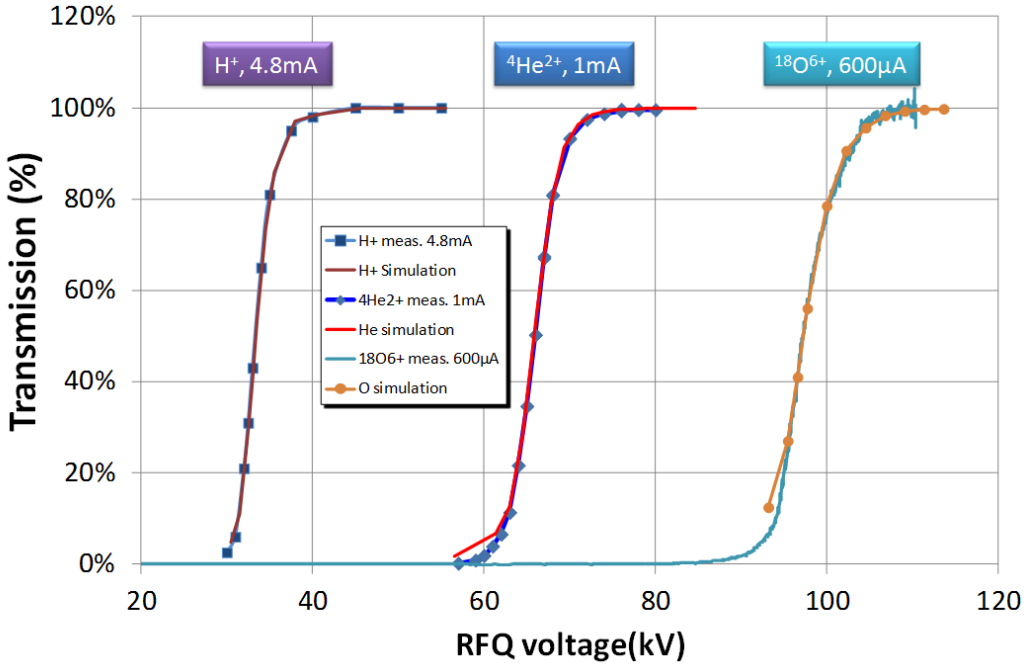
Mesures



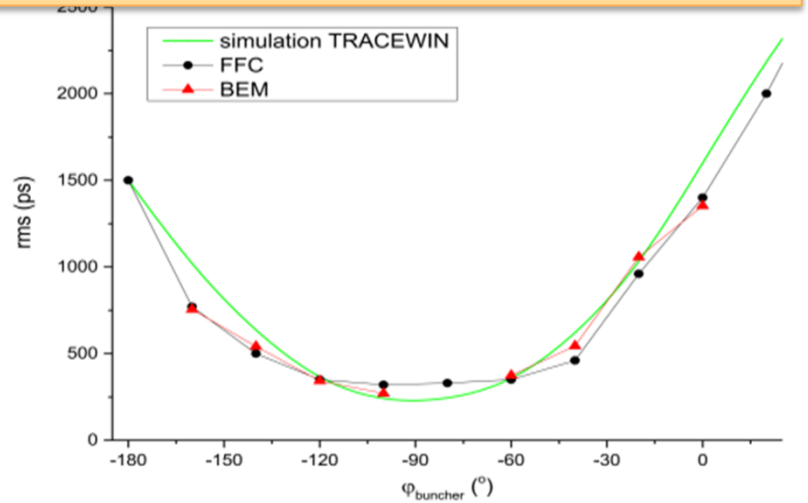


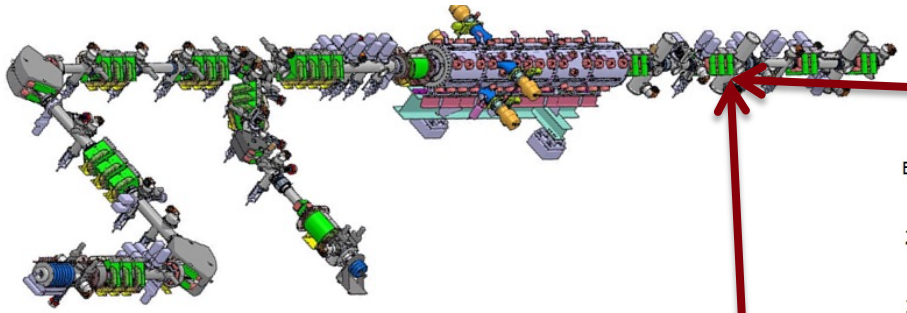
- Simulations et mesures à 40 mA
- Des différences visibles mais explicables,
- Le point d'injection du RFQ n'est pas optimal ( )

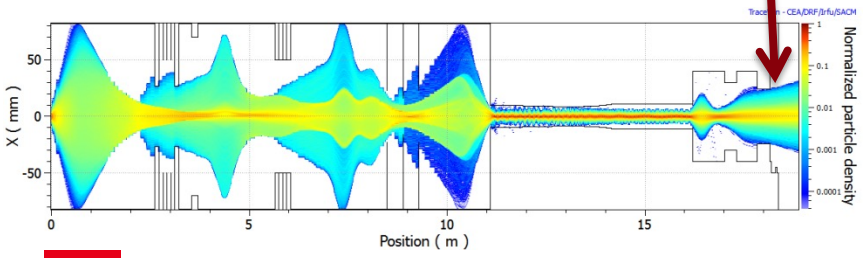
Validation expérimental, SPIRAL2



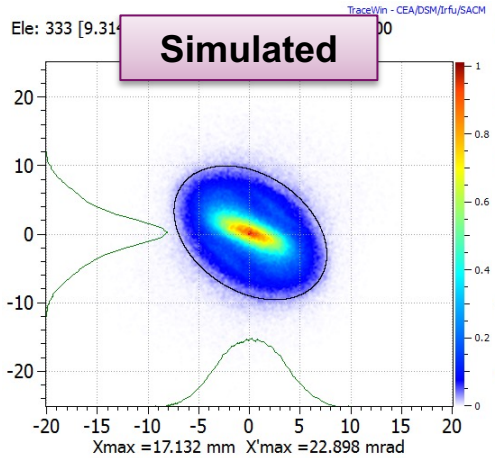
Largeur du bunch faisceau

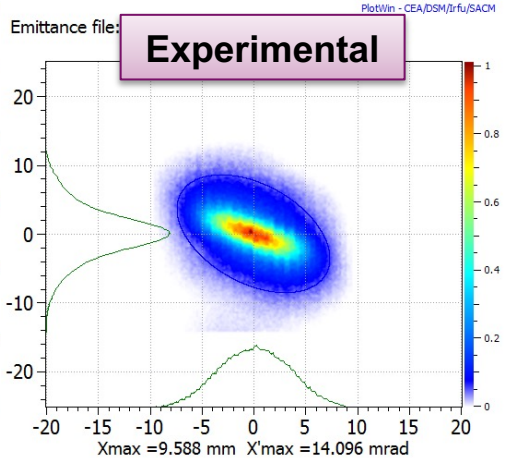






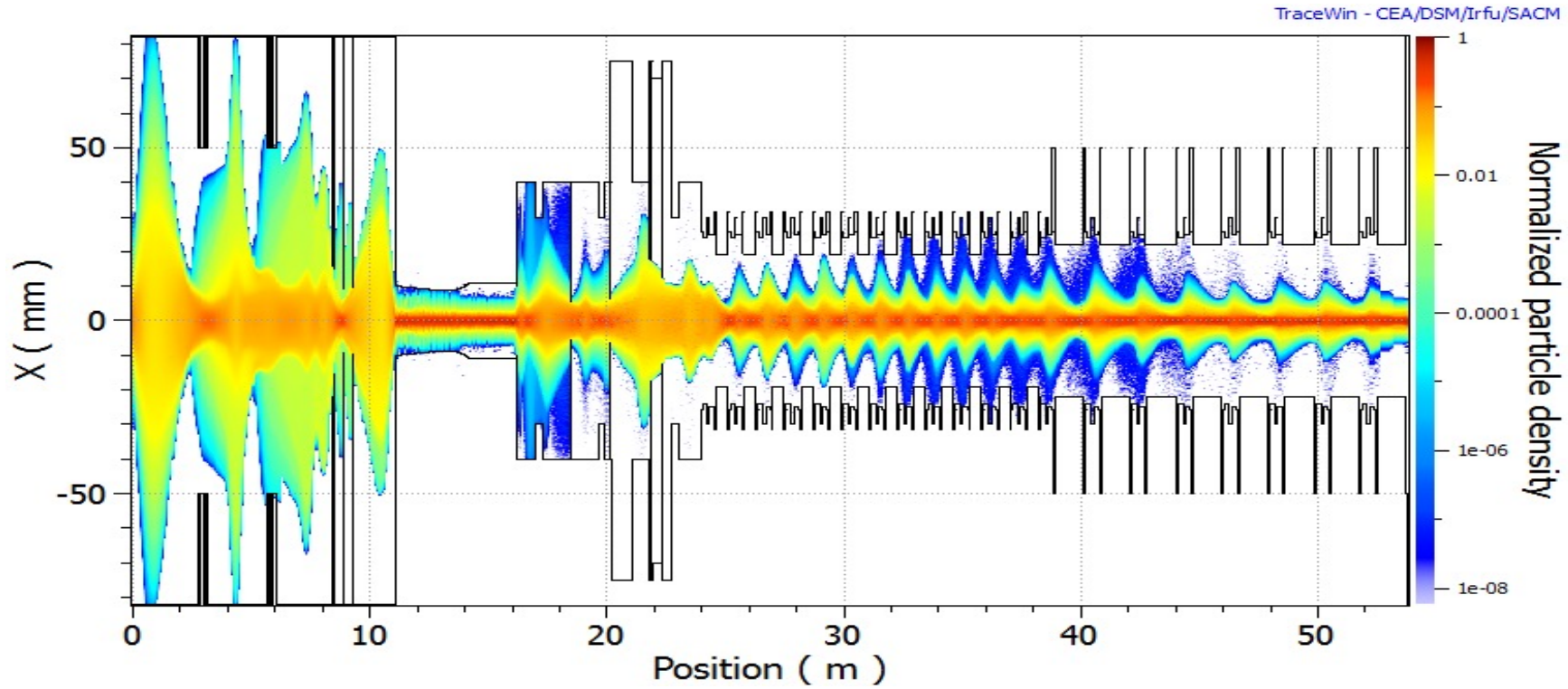
LME XX' emittance for proton beam @ 5 mA





Validation expérimental, SPIRAL2

Towards experimental halls



FROM RESEARCH TO INDUSTRY

www.cea.fr

Virtual accelerator

Didier URIOT

- Concept
- Modes de fonctionnement:
  - Autopilot
  - Control tower
  - Flight simulator
- PIP2-IT

VA Concept

SOME GENERALITIES ABOUT VA

A **virtual Accelerator** a simulation code connected with the control system of a real machine.
Virtual: because from the viewpoint of the control system, the simulation code is seen as a real machine.

Two different approaches to implement it:
- Integrate the simulation model into the control system (XAL @SNS, J-PARC…)
- Integrate a part of the control system into the simulation code (Trace3D)

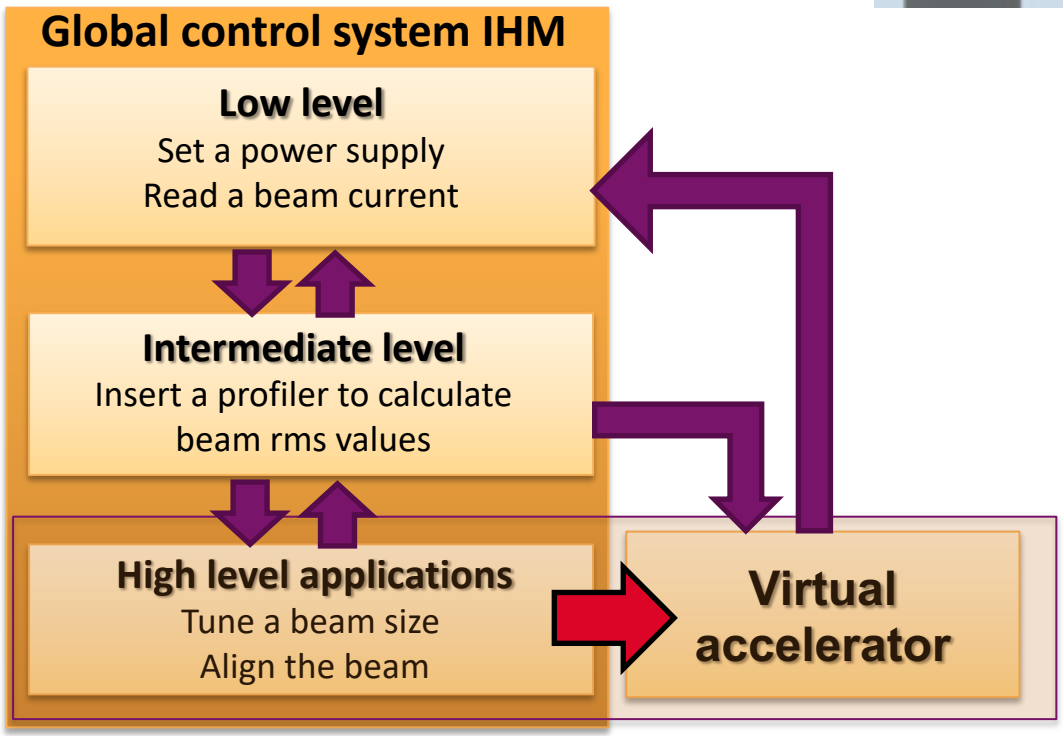
Two different groups involved:
- Beam dynamics group
- Control system group

In the second approach Virtual Accelerator is proposed and developed as an independent high level application and involving of control system group is not longer mandatory.

Requirements :
- Bi-directional connection / synchronization library between EPICS and code
- Very good predictive code
  → Accurate machine model

OPERATING MODES

Different operating modes have been identified
- **Autopilot**
- **Control tower**
- **Flight simulator**



LIMITATIONS

Duration of simulations:

Depending on the model used, the simulation of an accelerator is often not as fast as the real machine.

- In envelope mode: a few seconds
- In tracking mode: depends on the number of particles and the model used to describe the elements.

Today, it seems complicated to foresee the integration of RFQ in a virtual machine.

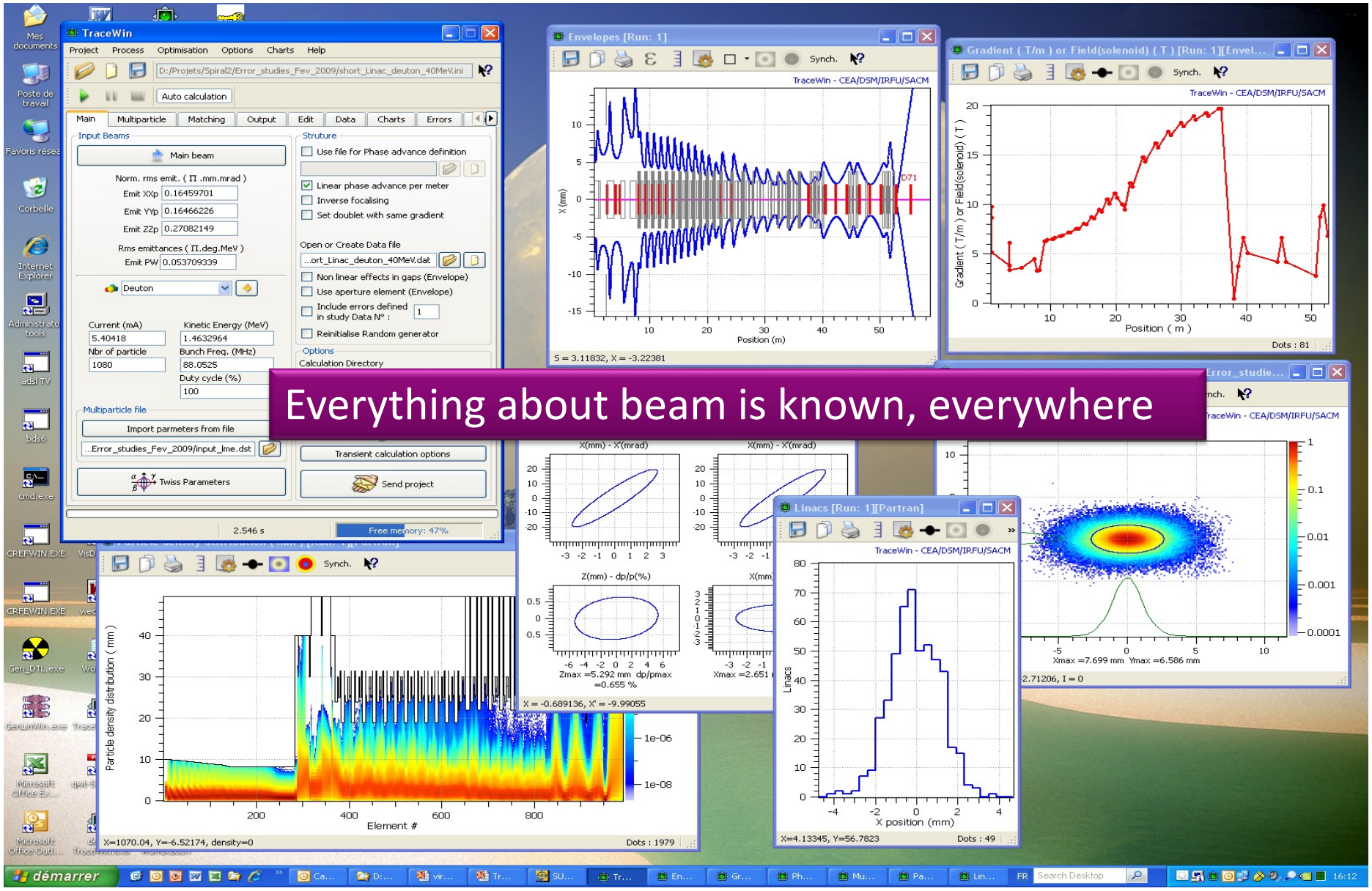
Predictability:

The higher the energy, the higher the quality of code predictability.

Safety:

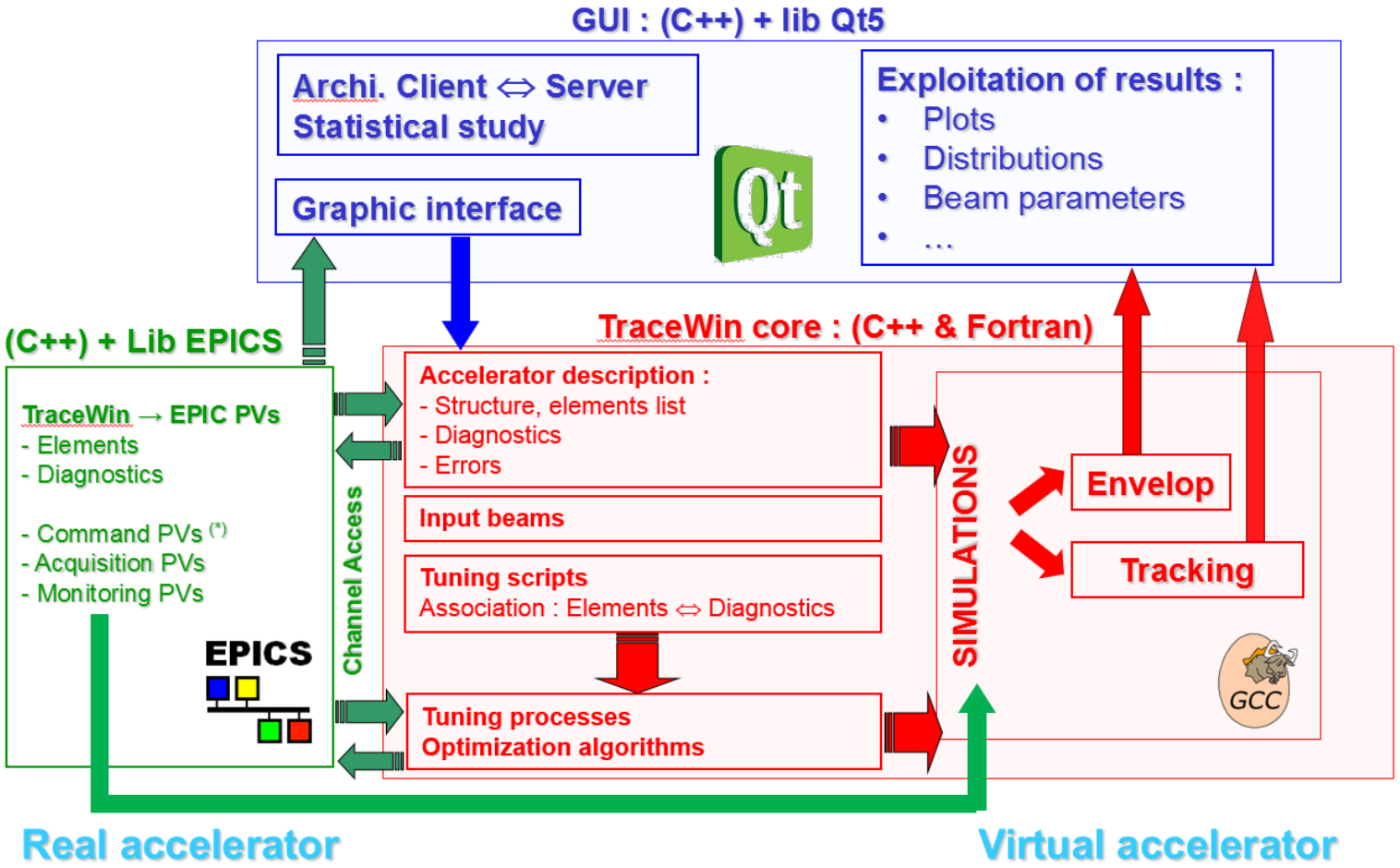
"*Autopilot*" mode for replacing high level applications by simulation code, seem ambitious for high power beam. Clearly, plug it into a MW machine is not for tomorrow. It's a huge challenge.

TRACEWIN CODE



TraceWin code + VA implementation

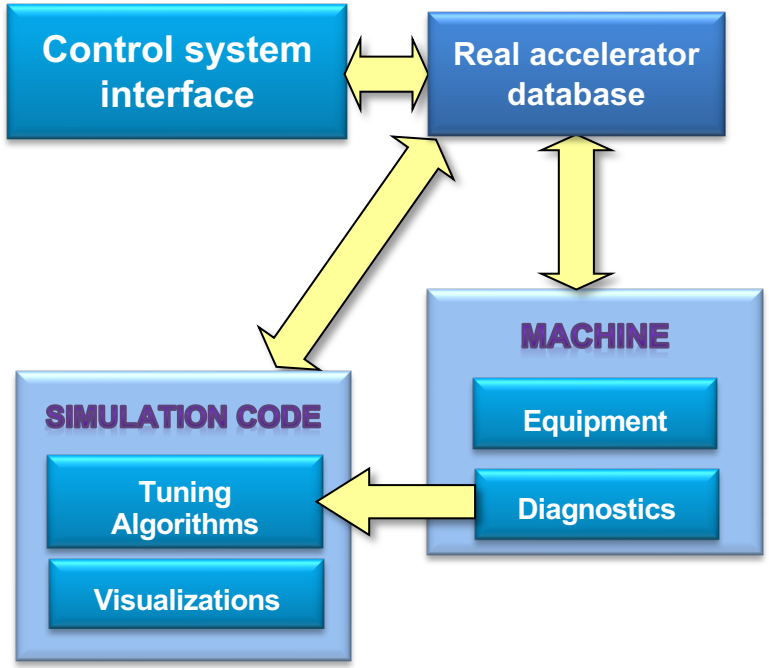
- 2 versions, nommées TraceWinVA, ont été développées pour Windows et Linux,
- Tous les développements ont été effectués en langage C++,
- Les codes sont entièrement autonomes et ne nécessitent pas l'installation de bibliothèques externes,
- Un ordinateur suffisamment puissant est obligatoire dans les salles de contrôle des accélérateurs.



(*) PROCESS VARIABLE

Autopilot mode

"AUTOPILOT" MODE



- Les paramètres de simulation peuvent être envoyés à l'accélérateur réel,
- Les codes modernes ont la capacité de régler la machine simulée en tenant compte uniquement des informations de diagnostic,
- Utiliser les fonctions automatiques du code pour régler directement la machine réelle,
- Dans ce mode, le système de contrôle HIM de la machine peut être remplacé par le code de simulation GUI,
- Le code utilise les mesures de diagnostic de la machine réelle comme entrée de son algorithme pour contrôler l'équipement de la machine réelle,
- Le code doit avoir un accès en lecture et en écriture à la base de données de la machine,
- **Le programme de modélisation n'est pas nécessaire ici.**

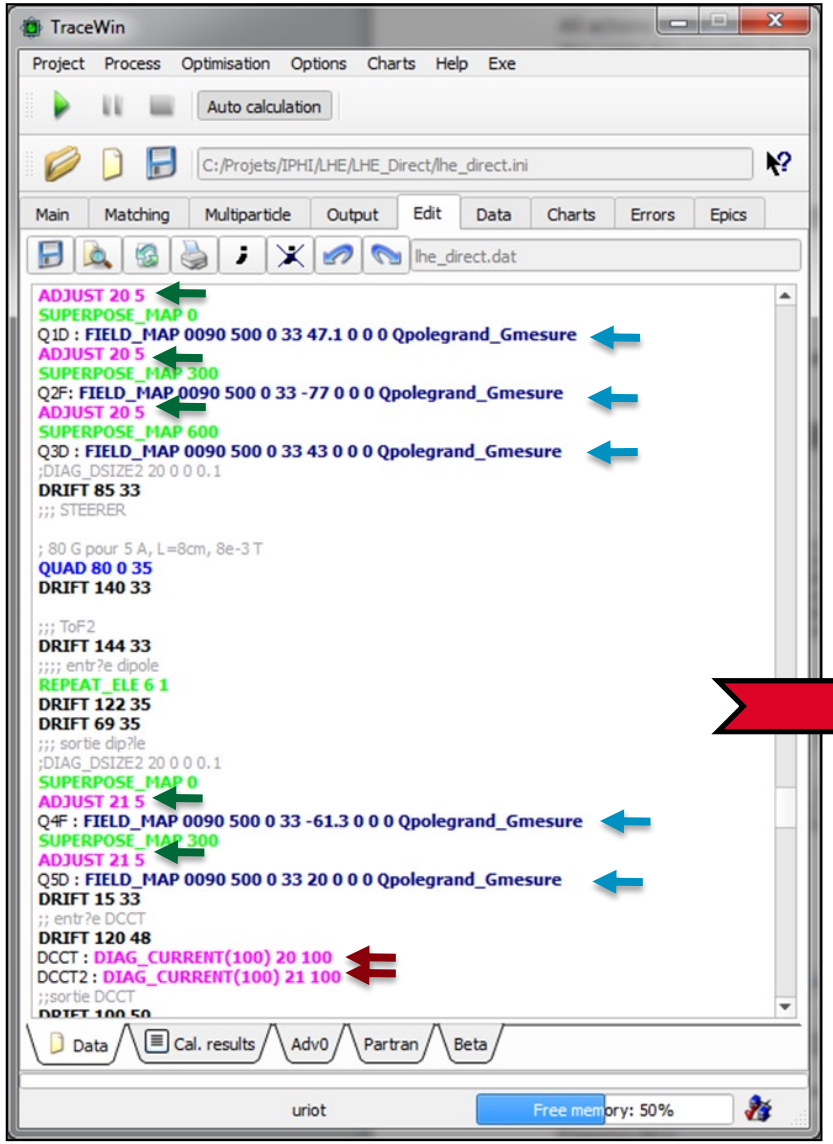
commissioning→ ***"Autopilot"*** mode was the priority, compensating high level tuning applications missing for IPHI and Spiral2

Injectors successfully commissioned thank to this mode since more than decade

- SILHI @ Saclay / SACM - *2006*
- LBE Spiral2 (light ions line) @ Saclay / SACM - *2012*
- LBE Spiral2 (heavy ions line) @ Grenoble / LPSC - *2012*

⟶ Clearly shown the interest of such a tool, especially for operation group

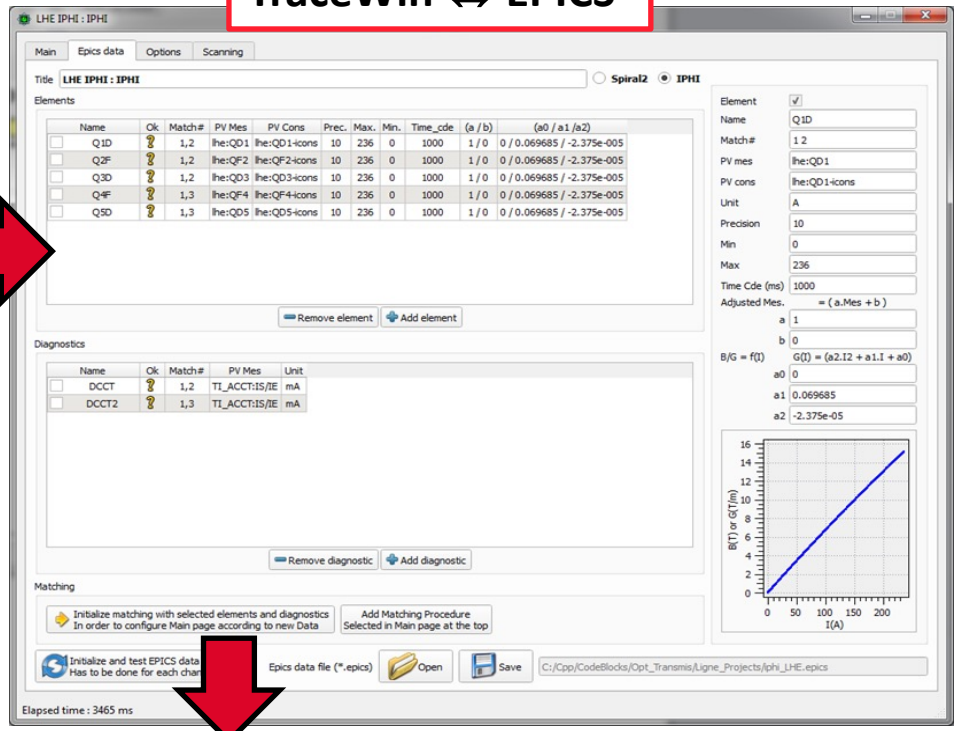
TRACEWIN VA, LES DONNÉES



Définition de la machine dans TraceWin:

- Les éléments magnétique et cavités.
- Les diagnostics
- Les procédures ou scripts de réglage

TraceWin ⇔ EPICS



TRACEWIN VA, LES DONNÉES

TEST_PROJECT

Main | Devices | Options

Title: TEST_PROJECT — Other / Spiral2 / IPHI

Elements

	Name	Ok	Type	Match#	PV Mes	PV Cons	Prec.	Max.
☐	QF1	☺	Magnetic	4,5	lhe:QD1-Imes	lhe:QD1-Icons	0.001	250
☐	QF3	☺	Magnetic	4,5	lhe:QD1-Imes	lhe:QD1-Icons	0.001	250
☐	QD2	☺	Magnetic	4,5	lhe:QD1-Imes	lhe:QD1-Icons	0.001	250
☐	REB1	☺	Cav Field	---	lhe:REB1-Emes	lhe:RBE1-Econs	0.01	1e+06
☐	REB1	☺	Cav Phase	---	lhe:REB1-Emes	lhe:RBE1-Econs	0.01	1e+06

Diagnostics

	Name	Ok	Match#	PV Mes	PV Simul	Unit
☐	PROF1X	?	4	lhe:Prof1.x		mm
☐	PROF1Y	?	4	lhe:Prof1.y		mm
☐	PROF2X	?	5	lhe:Prof2.x		mm

Remove | Add | ReInitialize

Type element: MAGNETIC

Name	QD2
Match#	4 5
PV mes	lhe:QD1-Imes
PV Cons	lhe:QD1-Icons
Unit	A
Precision	0.001
Min	0
Max	250
Time Cde (ms)	1000

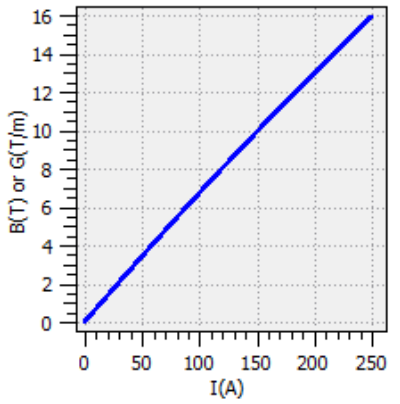
Adjusted Mes. Mes = (a.PVmes + b)

a: 0 b: 1

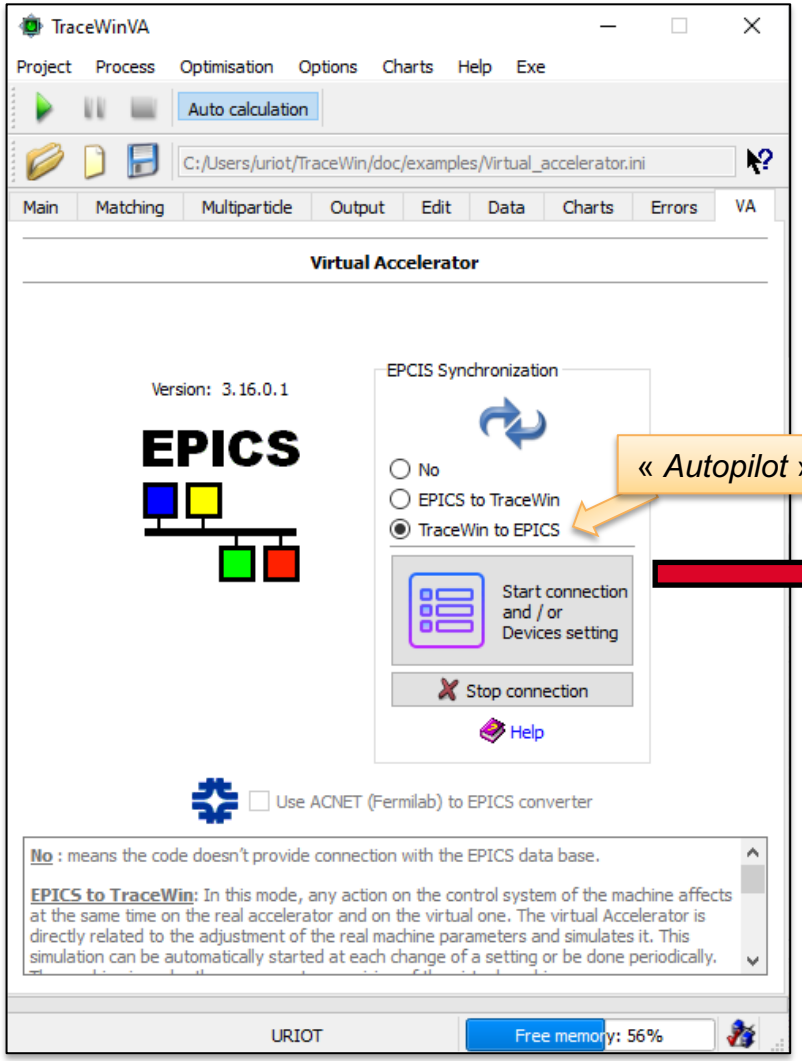
B/G = f(I) $G(I)=a_3.I^3+a_2.I^2+a_1.I+a_0$

a_0: 0 a_1: 0.069685

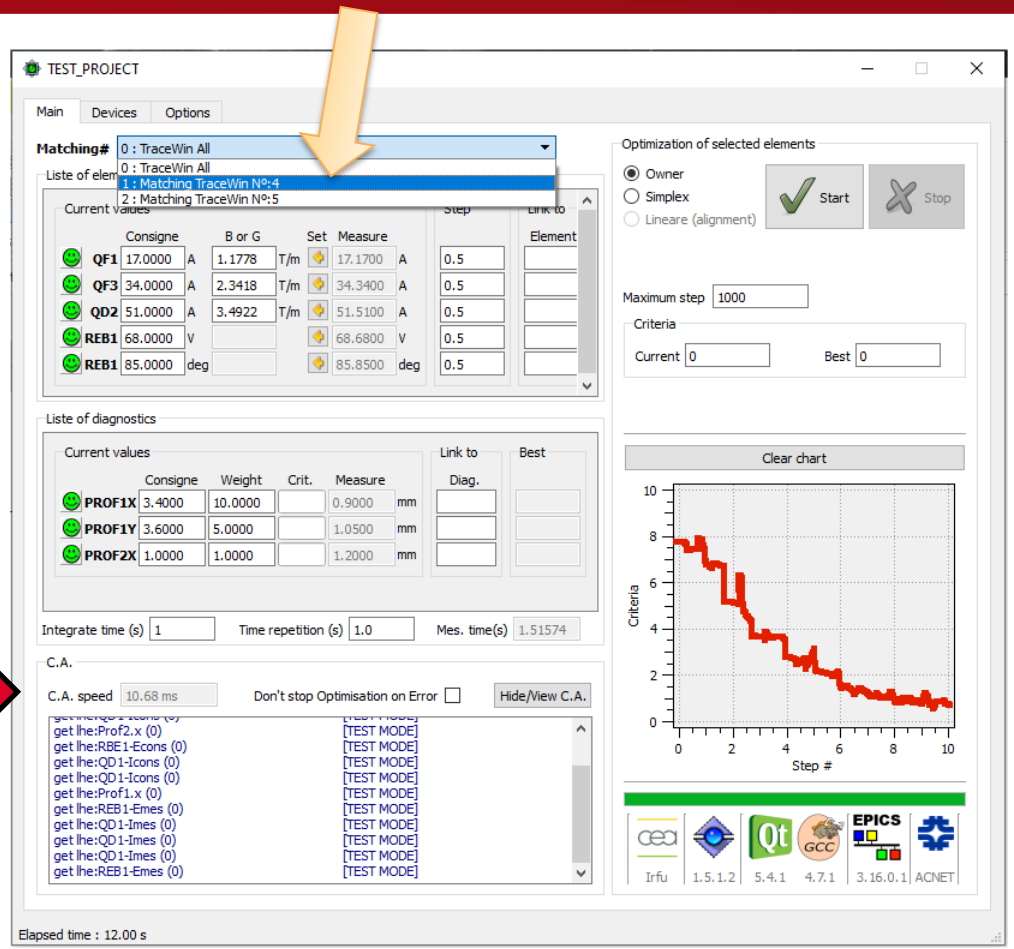
a_2: -2.375e-05 a_3: 0



TraceWinVA data base GUI

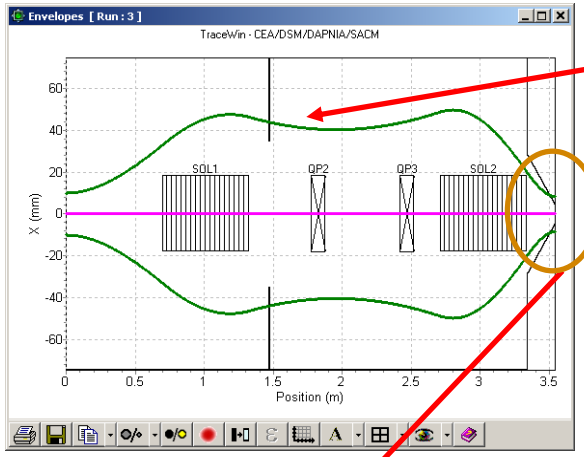


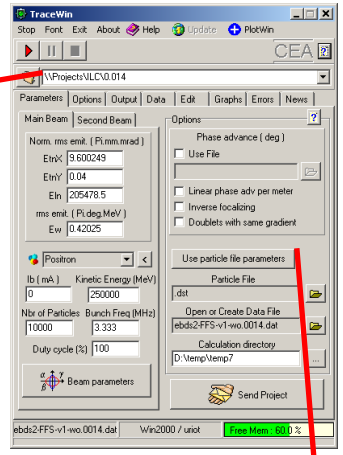
« *Autopilot* »



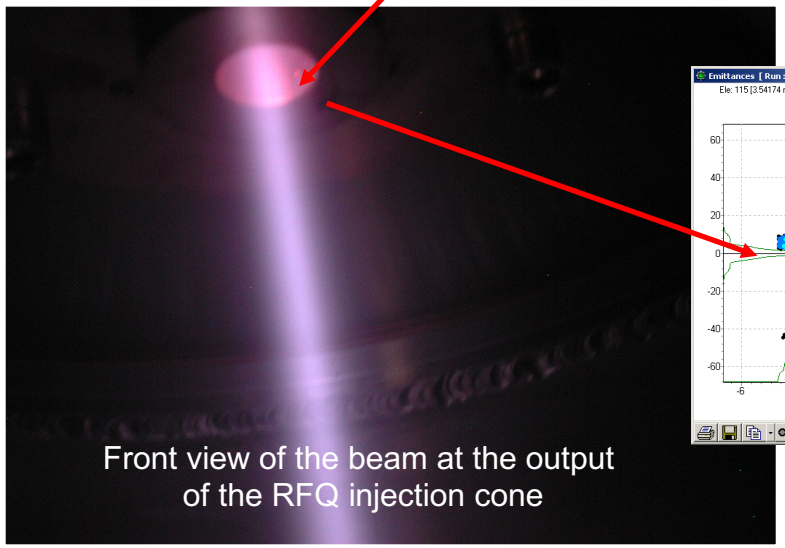
- TraceWin n'est donc utilisé ici que comme descriptif de la machine et des procédures de réglages.
- Ses algorithmes de tuning sont aussi utilisés.
- Application à la vrai machine l'ensemble des réglages testé en simulation.

FIRST TEST, SILHI (2006)

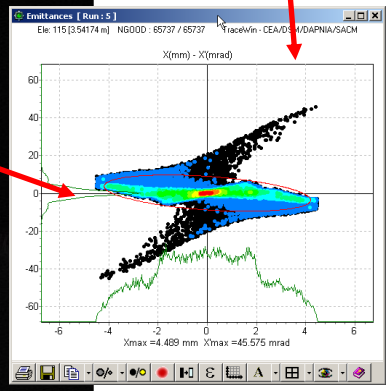




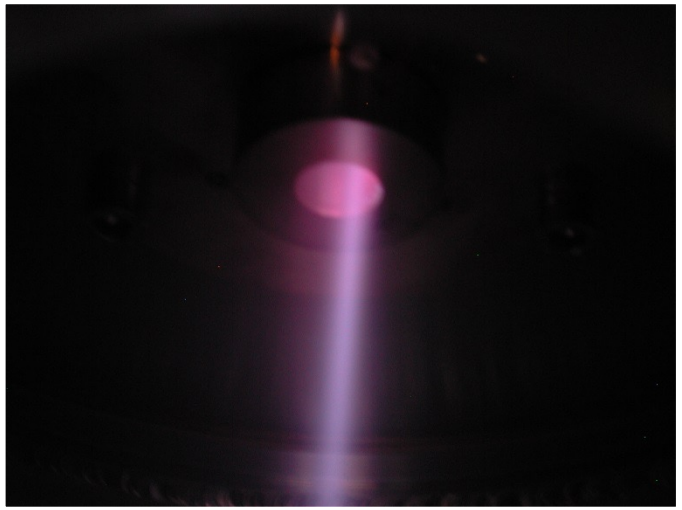
- Beam injection through the cone have been optimized.
- Beam parameters of RFQ injection have been validated
- It's planned to use VA to tune LEBT+RFQ+HEBT.



Front view of the beam at the output of the RFQ injection cone

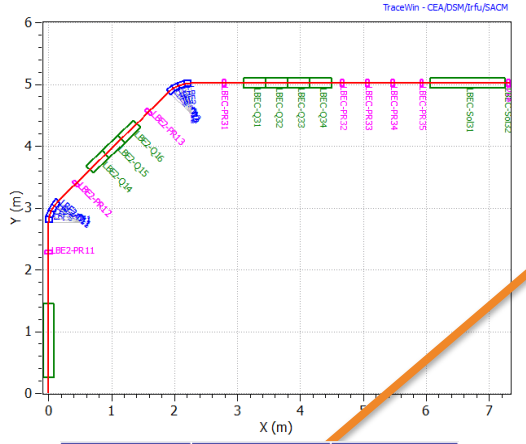


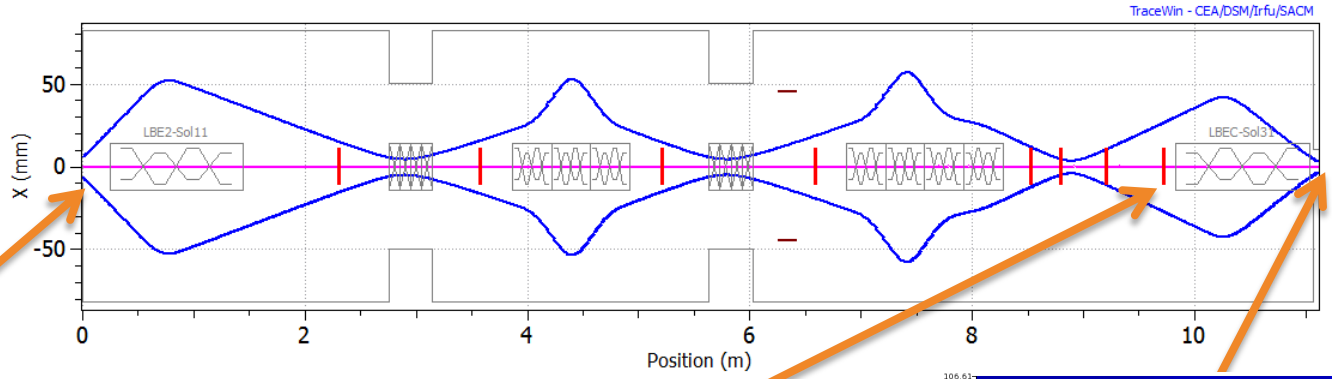
VA, 10 minutes, 90%



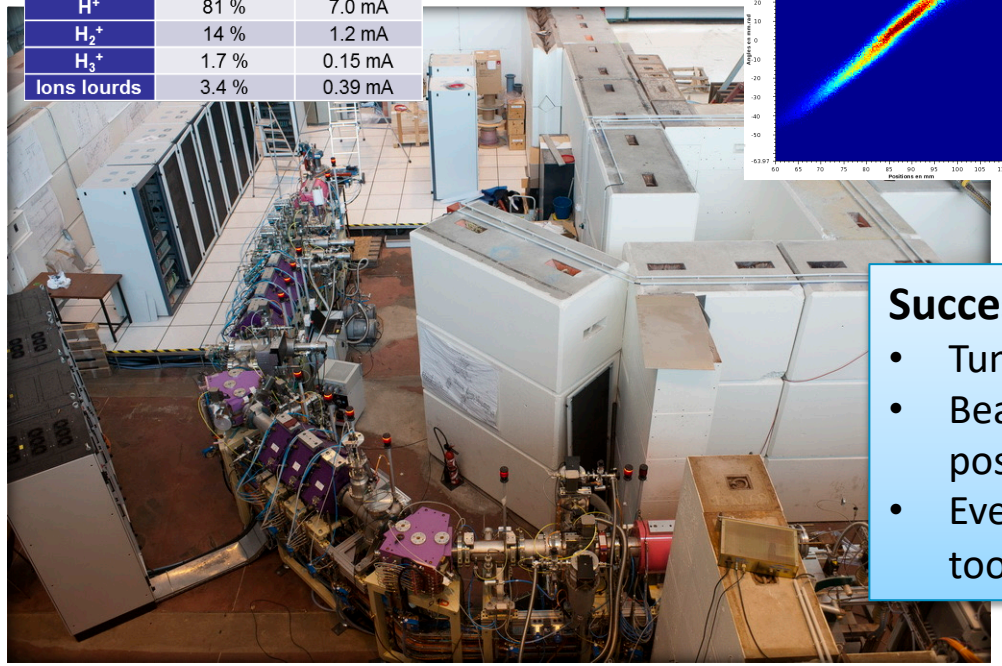
Manually, 1 day, 80%

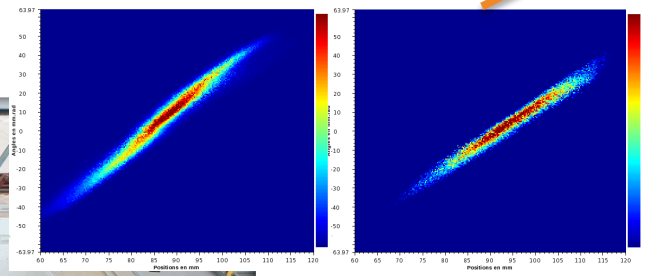
SPIRLA2 LBE LIGHT IONS LINE @ SACLAY (2012)

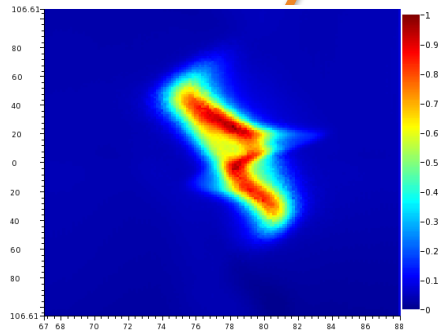




Ion	Proportion	Courant
Ions	100 %	8.7 mA
H^+	81 %	7.0 mA
H_2^+	14 %	1.2 mA
H_3^+	1.7 %	0.15 mA
Ions lourds	3.4 %	0.39 mA



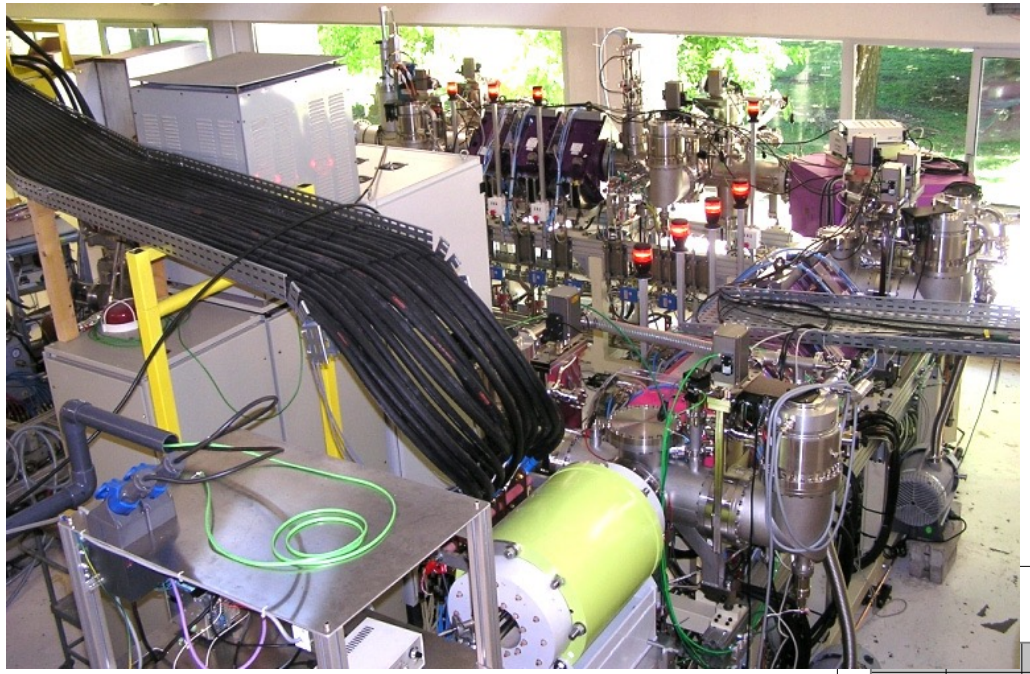


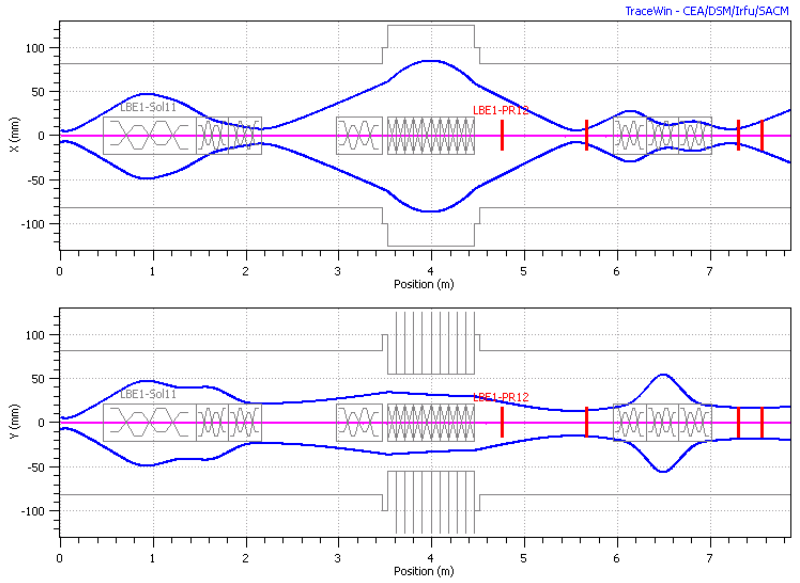


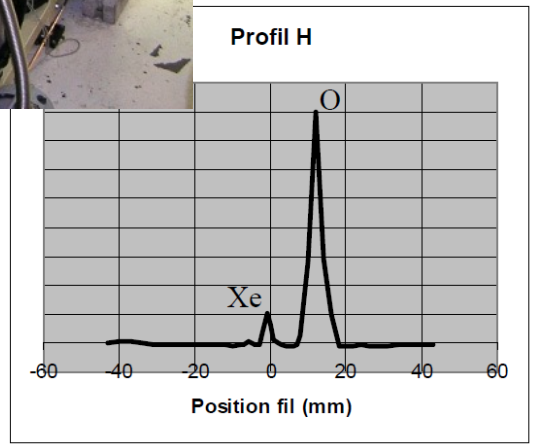
Successfully commissioned (2 years)

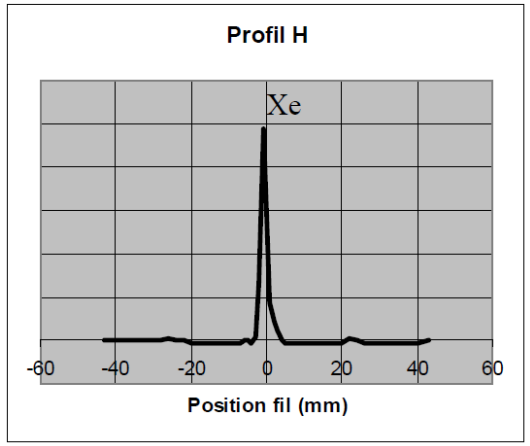
- Tuning procedures defined in TraceWin validated.
- Beam entrance in RFQ measured at the exact RFQ position and conform to predictions.
- Everything has been performed using "*autopilot*" tools

SPIRLA2 LBE HEAVY IONS LINE @ LPSC (2012)



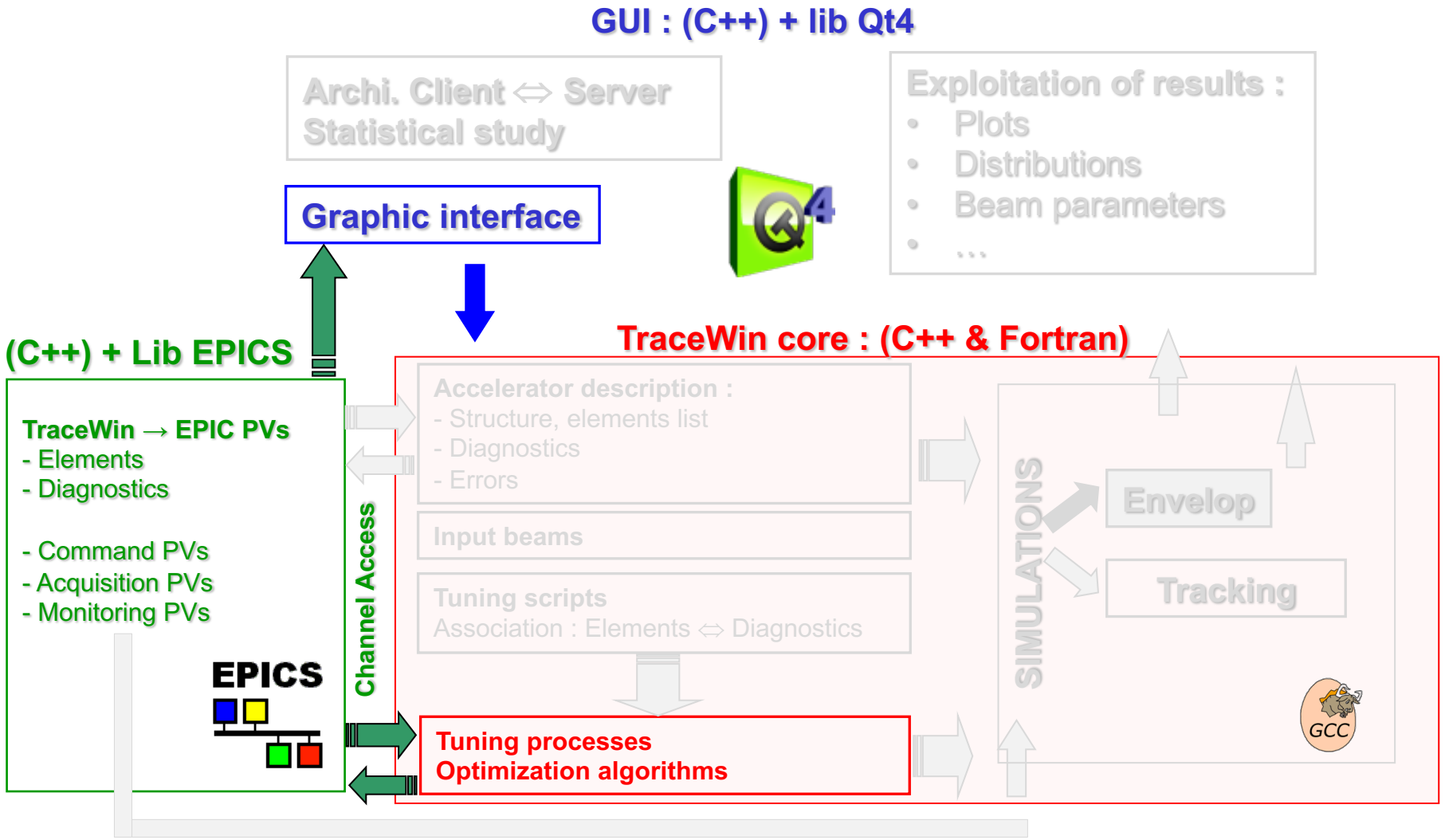






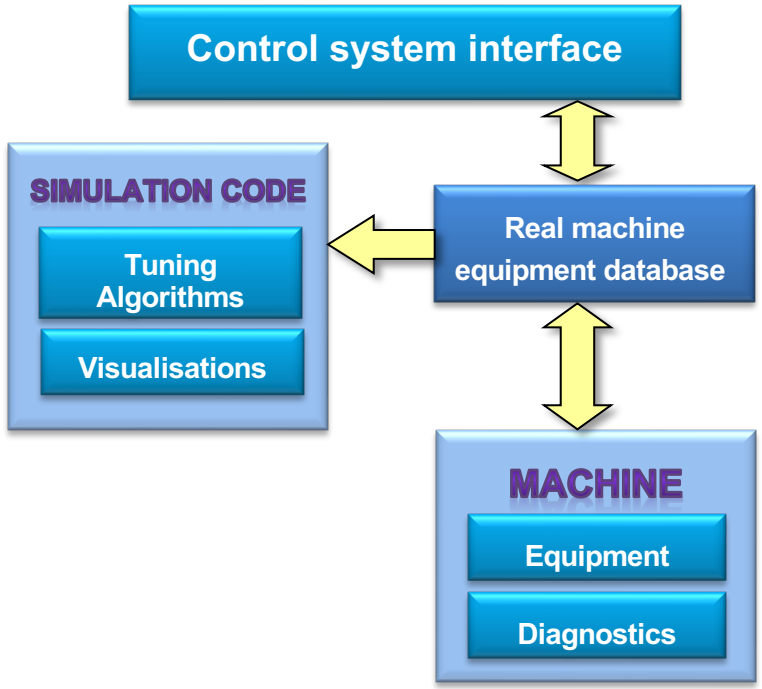
Successfully commissioned
The separation power of the optical system has been validated

FIRST STEP OF "*AUTOPILOT*" MODE



Control tower mode

"CONTROL TOWER" MODE



- Une action sur le système de commande de la machine agit en même temps sur l'accélérateur réel et sur l'accélérateur virtuel.
- Synchronisation automatique ou périodique
- La machine est sous la surveillance constante de la machine virtuelle. Elle est surveillée par le code de simulation
- Le code de l'accélérateur virtuel n'a besoin que d'un accès en lecture à la base de données de l'accélérateur.

2017- 2018 developments

- First test on IPHI injectors - *2018*
- SPIRAL2 en 2019

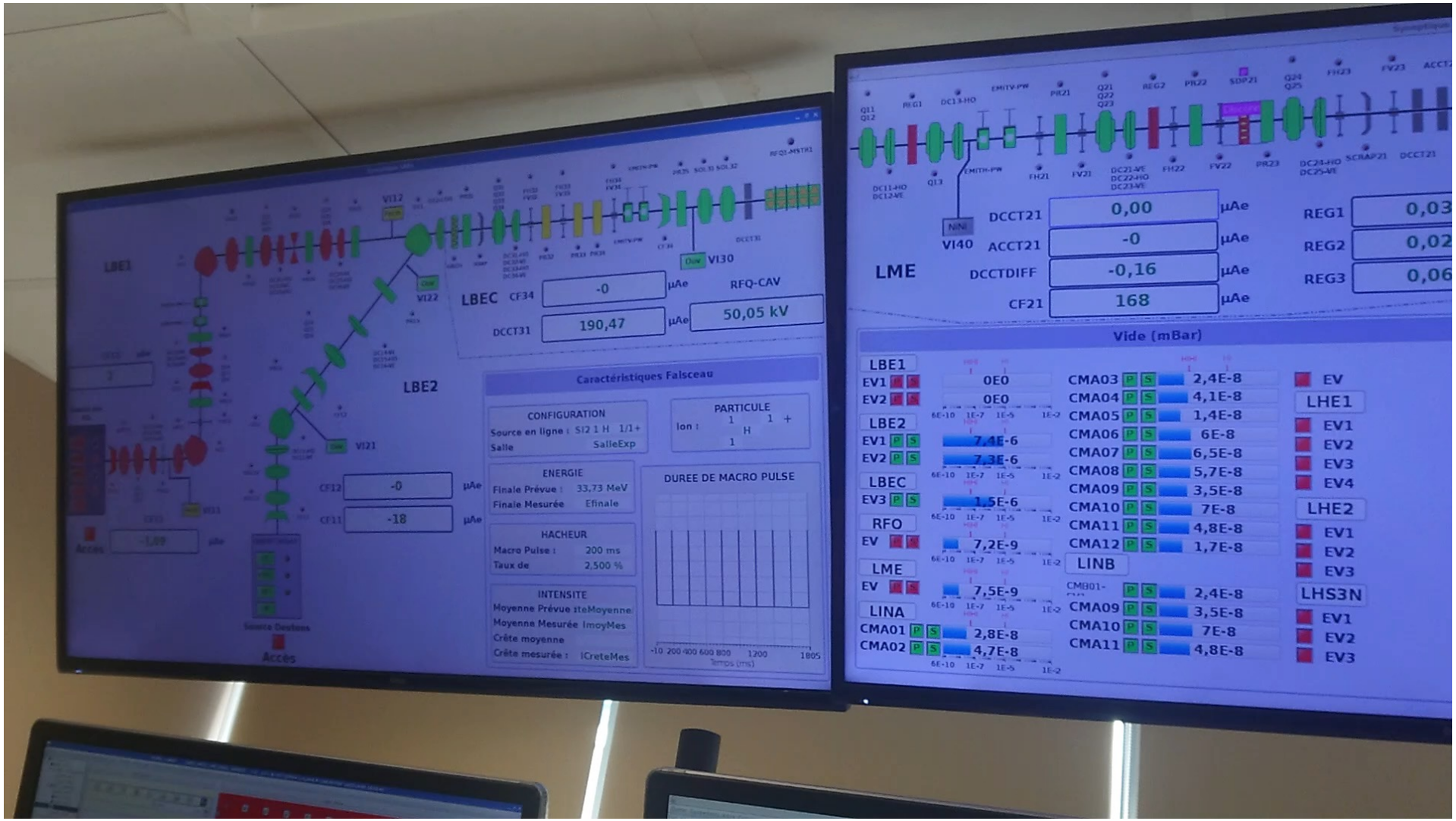
"CONTROL TOWER" MODE TEST

Control Tower mode has be integrated at the end of 2017.

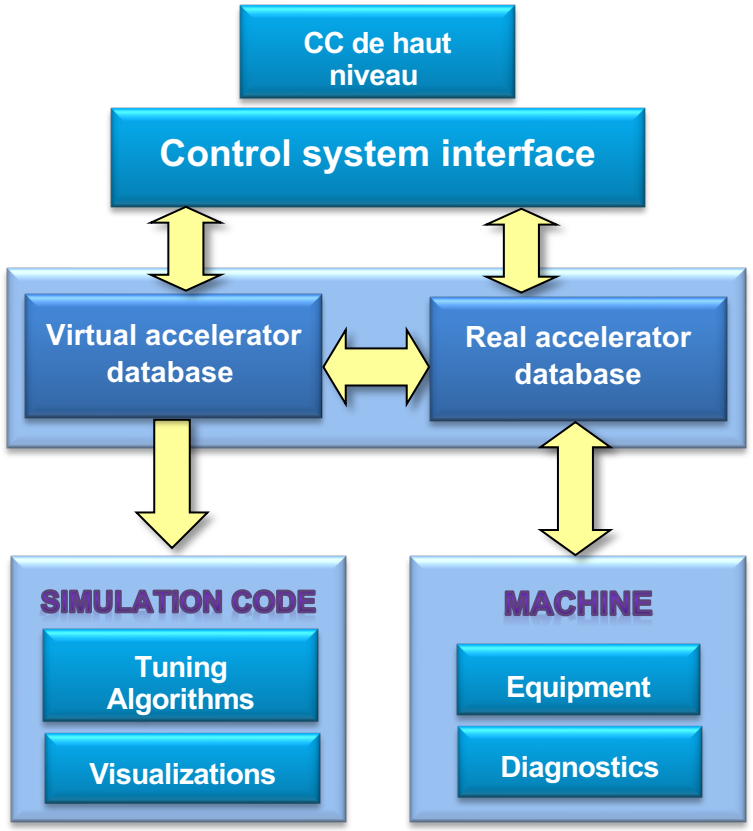
So, all PVs are monitored and synchronized with the VA,
When during operation of the real accelerator an element setting is changed in the control system, the simulation is automatically redone and the output charts are refreshed in the same time.

- In this way, an operator can continuously view the state of the beam and its main parameters,
- A comparison with measurements from diagnostics can thus allow a deep monitoring of the accelerator behavior,
- A significant discrepancy must alert the operator that something is wrong.

"CONTROL TOWER" MODE TEST



"FLIGTH SIMULATOR" MODE



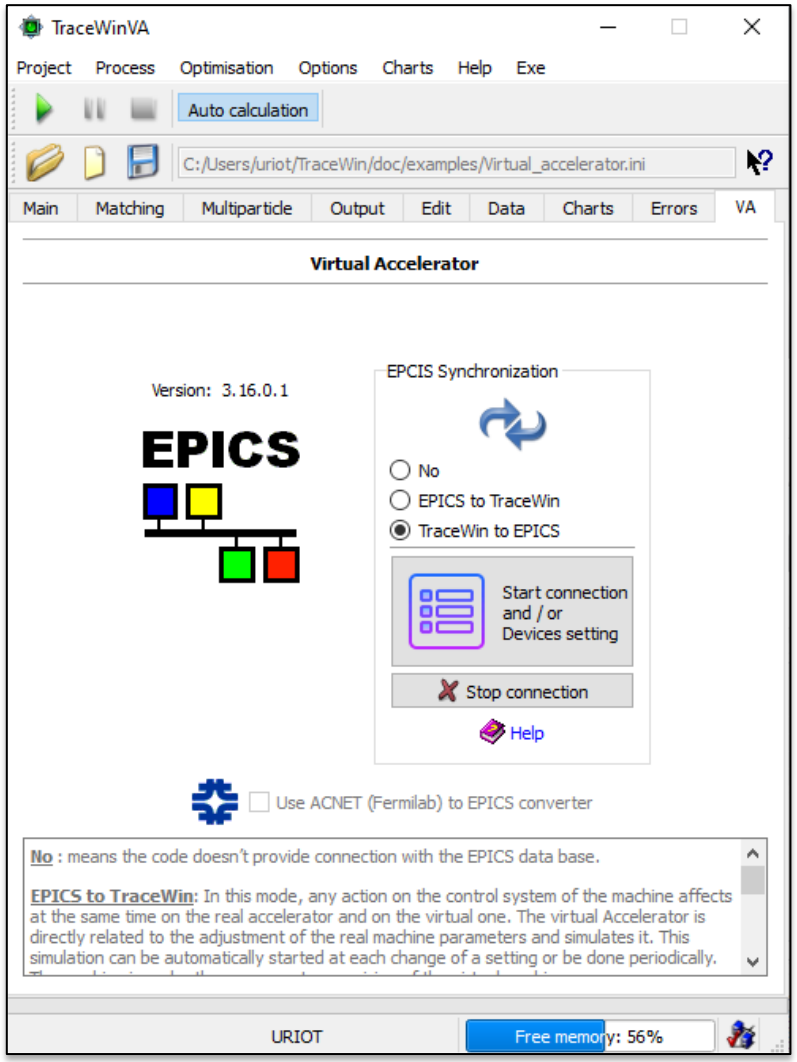
- L'action sur le contrôle commande est appliquée soit à l'accélérateur virtuel, soit à l'accélérateur réel.
- Il existe en fait deux machines distinctes : l'accélérateur réel et son simulateur ou VA.
- Cela implique 2 bases de données indépendantes ou une seule base de données contenant des champs séparés représentant les états et les valeurs des dispositifs des machines réelles et virtuelles.
- Le système de contrôle HIM doit permettre de passer facilement et en toute sécurité d'une base de données à l'autre.
- éventuellement de copier une base de données sur l'autre.
- Le code de simulation n'a besoin que d'un accès en lecture à la base de données virtuelle
- Doit être pensé au moment du développement du système de contrôle commande.

Implémenté dans TraceWinVA uniquement pour les diagnostics ou 2 champs différents selon la machine sont prévus.

Intérêt: tester les procédures de réglages haut niveau du CC sur la machine virtuelle

TraceWin implementation

TraceWinVA main GUI



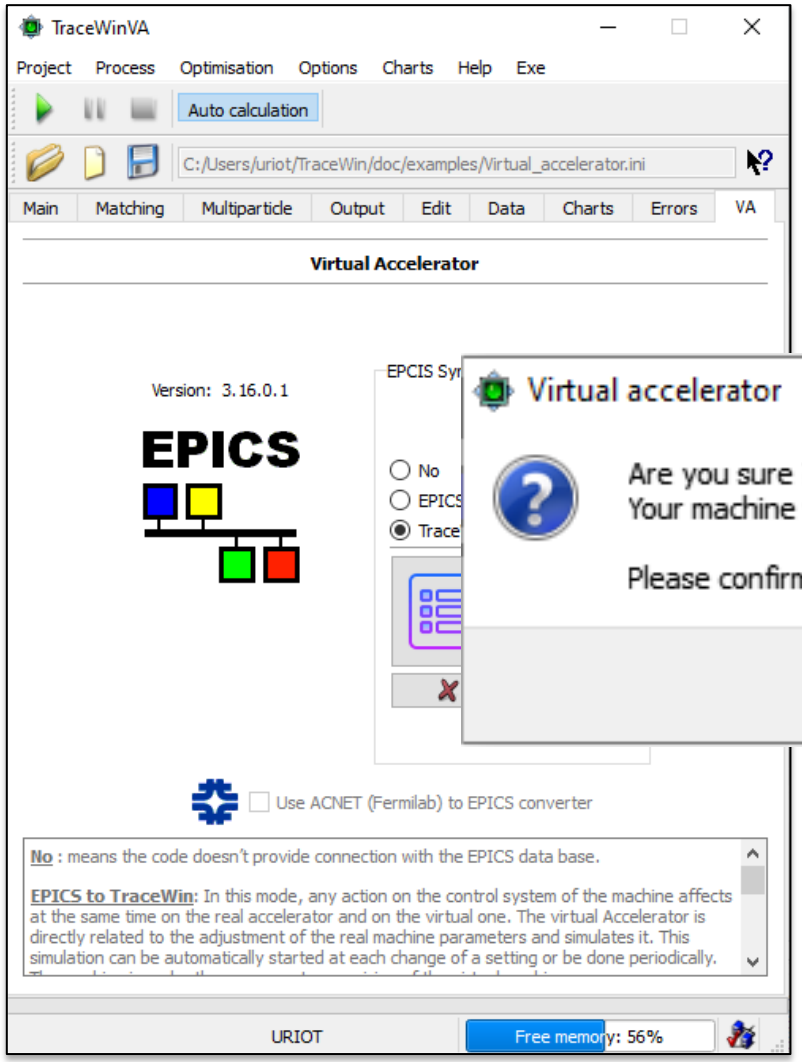
No : means the code doesn't provide connection with the EPICS data base,
EPICS to TraceWin corresponds to the "*Control tower*" & "*Flight simulator*" modes
TraceWin to EPICS corresponds "*Auto-pilot*" mode.

When a connected mode is selected a button "***Stop connection***" allows to break this link to come back to an usual standalone simulation code.

Button "***Epics Elements***" provides the tools allowing to visualize and initialize the common elements defined in TraceWinVA code and in EPICS data base.

Use ACNET : ACNET to EPICS converter developed for PIP2-IT

TraceWinVA main GUI



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Use ACNET : ACNET to EPICS converter developed for PIP2-IT

Merci de votre attention

Remarques ou commentaires ?

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