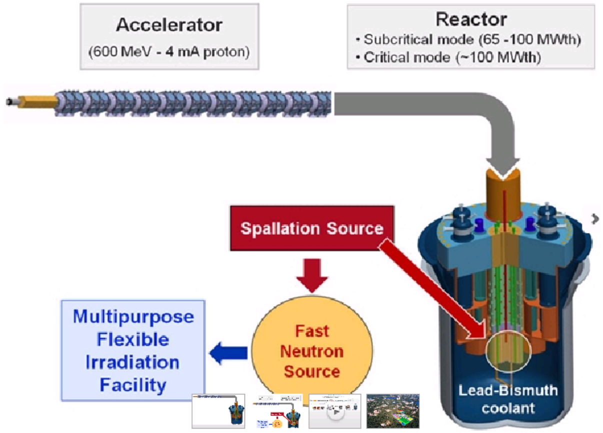
Workshop : Non-linear beam expander systems in high-power accelerator facilities
ISA, Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark
26th and 27th March 2012

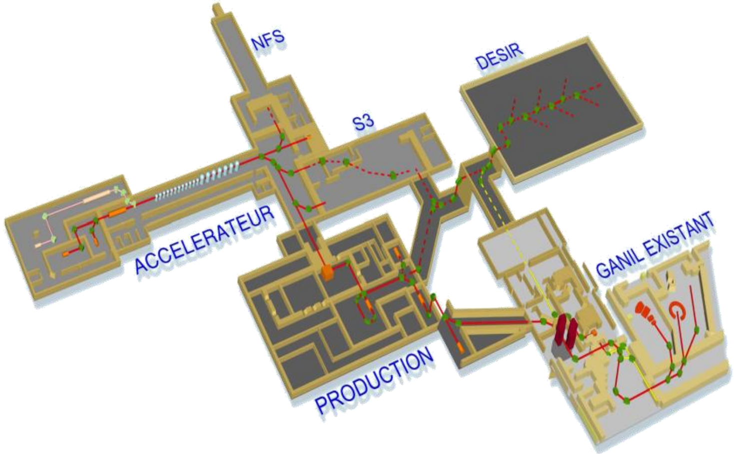
➢ Aspects of he MYRRHA project

http://myrrha.sckcen.be/en
The Central Design Team for a fast spectrum transmutation experimental facility

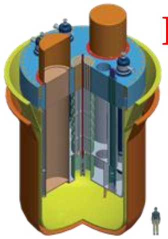


➢ SPIRAL2 : some key about the beam furniture on targets

http://www.ganil-spiral2.eu/
A new accelerator for GANIL
at Caen France



L. Perrot : perrot@ipno.in2p3.fr , CNRS-IN2P3-IPNO



What is MYRRHA ?

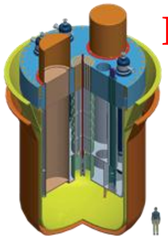
Multi-purpose hybrid research reactor for high-tech applications

SCK•CEN, the Belgian Nuclear Research Centre in Möl has been working for several years on the design of a multi-purpose irradiation facility in order to replace the ageing BR2 reactor, a multi-functional materials testing reactor (MTR), in operation since 1962.

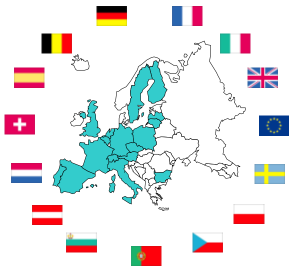
MYRRHA, a flexible fast spectrum research reactor (50-100 MWth) is conceived as an accelerator driven system (ADS), able to operate in sub-critical and critical modes. It contains a proton accelerator of 600 MeV, a spallation target and a multiplying core with MOX fuel, cooled by liquid lead-bismuth (Pb-Bi).

MYRRHA will be located in Möl Belgium operational at full power around 2023.

MYRRHA will be the ADS demonstrator



Where are R&D programs for the accelerator to MYRRHA ?



- The Central Design Team (**CDT**) for a fast spectrum transmutation experimental facility (**FASTEF**). It is the next step next after FP6 IP-EUROTRANS. European program : 2009-2012.

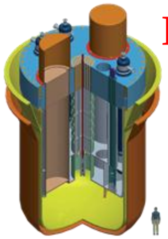
"FASTEF is proposed to be designed to an advanced level for decision to embark for its construction at the horizon of 2012 with the following objectives: to demonstrate the ADS technology and the efficient transmutation of high level waste; to operate as a flexible irradiation facility; to contribute to the demonstration of the Lead Fast Reactor technology without jeopardising the above objectives"

SEVENTH FRAMEWORK PROGRAMME

- The Myrrha Accelerator eXperiment (**MAX**) : http://ipnweb.in2p3.fr/MAX/

"To feed its sub-critical core with an external neutron source, the MYRRHA facility requires a powerful proton accelerator (600 MeV, 4 mA) operating in continuous mode, and above all featuring a very limited number of unforeseen beam interruptions. The MAX team, made up of accelerator and reliability experts from industries, universities and research organizations, has been set up to respond to these very specific twofold specifications."

CDT = R&D reactor+HEBT MAX = R&D accelerator



CNRS contribution to the CDT project

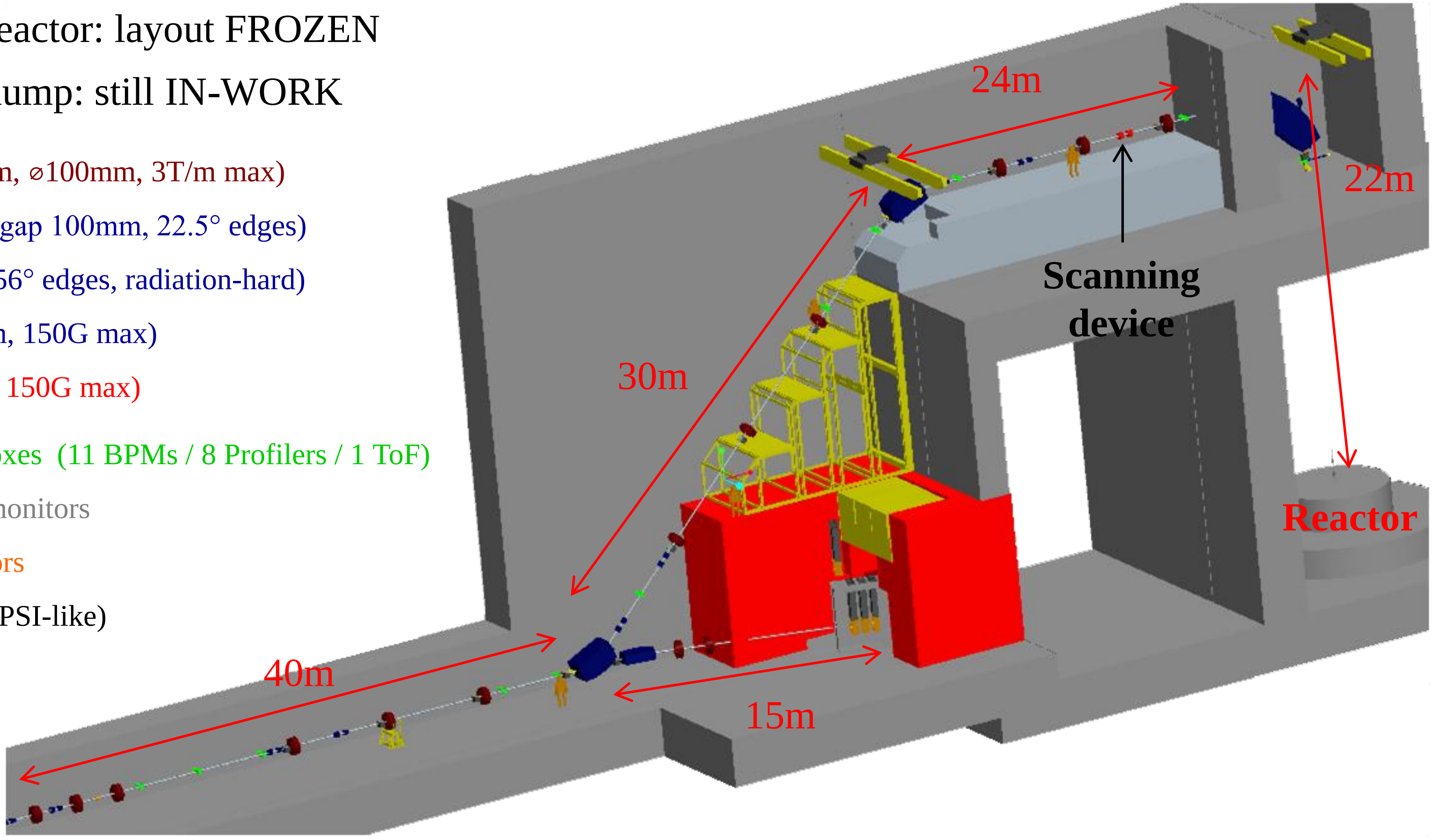
CDT Project

Beam line: status on general layout & optics WP2 Task 2.4

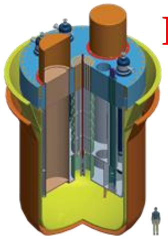
J-L. Biarrotte, L. Perrot, H. Saugnac

- General layout compatible with reactor building
- Beam line to reactor: layout FROZEN
- Beam line to dump: still IN-WORK

- 13 quadrupoles (L=0.5m, ⌀100mm, 3T/m max)
- 2 dipoles 45° (ρ=3.2m, gap 100mm, 22.5° edges)
- 1 dipole 90° (idem, 26.56° edges, radiation-hard)
- 16 DC steerers (L=0.3m, 150G max)
- 2 AC steerers (L=0.3m, 150G max)
- 11+ beam diagnostic boxes (11 BPMs / 8 Profilers / 1 ToF)
- 12 Collimators / Halo monitors
- 2 Beam Current Monitors
- 1 Near-Target Profiler (PSI-like)

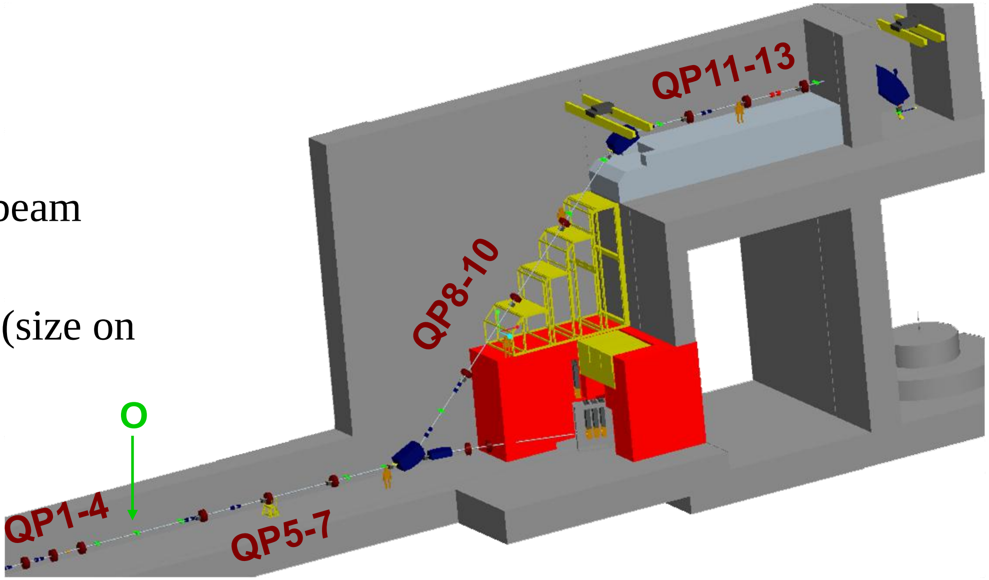


CDT project : beam line to reactor



By construction, the line:

- is achromatic at 1st order (position & divergence on target independent of beam energy)
- has telescopic properties at 1st order (size on target = 9 x size at point 0)

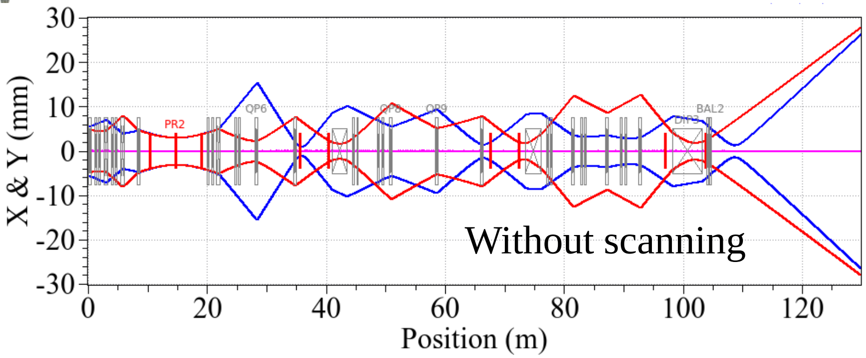


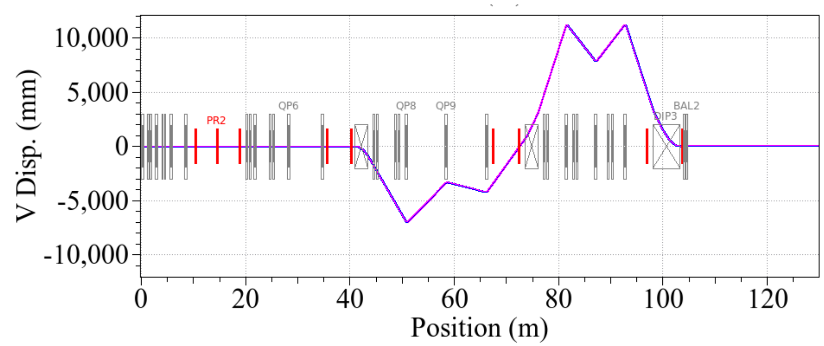
Tuning method :

1. Set the magnets to their theoretical value, & send a very low duty cycle beam
2. Adjust DC steerers for orbit correction (alignment)
3. Adjust QP1-4 => tune beam waist on 0 w/ desired size (1mm rms)
4. Adjust QP8-13 => optimize achromaticity
5. Adjust QP 5-7 => adjust desired beam size on target (9mm rms)
6. Recheck alignment & switch on + tune AC steerers on target
7. Increase step by step the beam duty cycle

CDT project : beam line to reactor

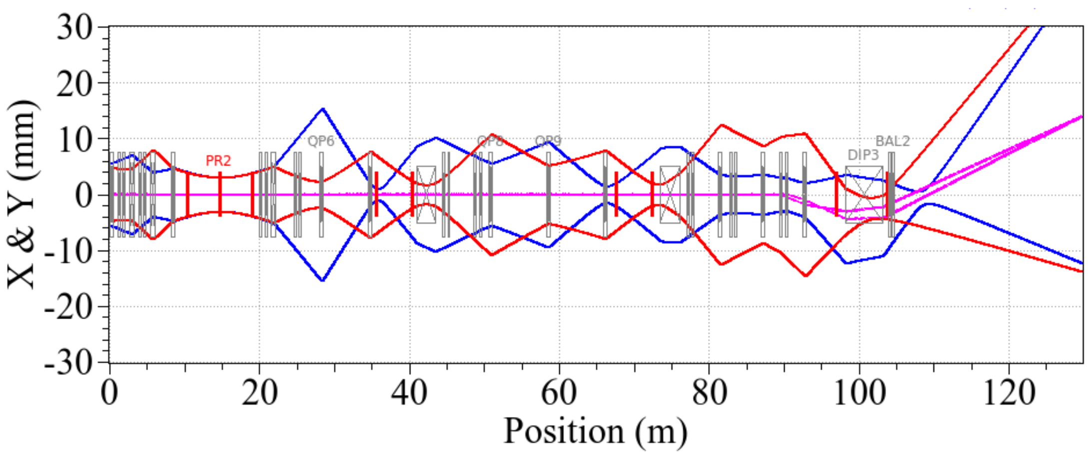
600MeV Protons beam envelopes at 3RMS

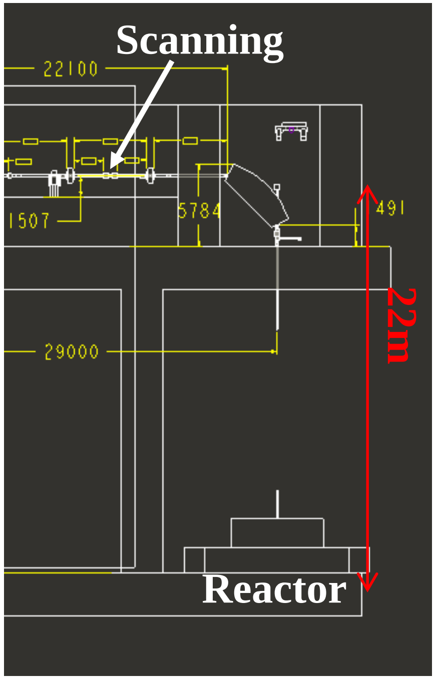


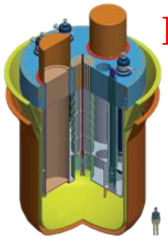


- ➢ Beam scanning must be done in order to protect the Pb-Bi target window
- ➢ No space is involved inside the reactor hall
- ➢ Safety do not permit to install the scanning device after the last 90° dipole

Device have to be located along the last deviation section







MYRRHA / CDT

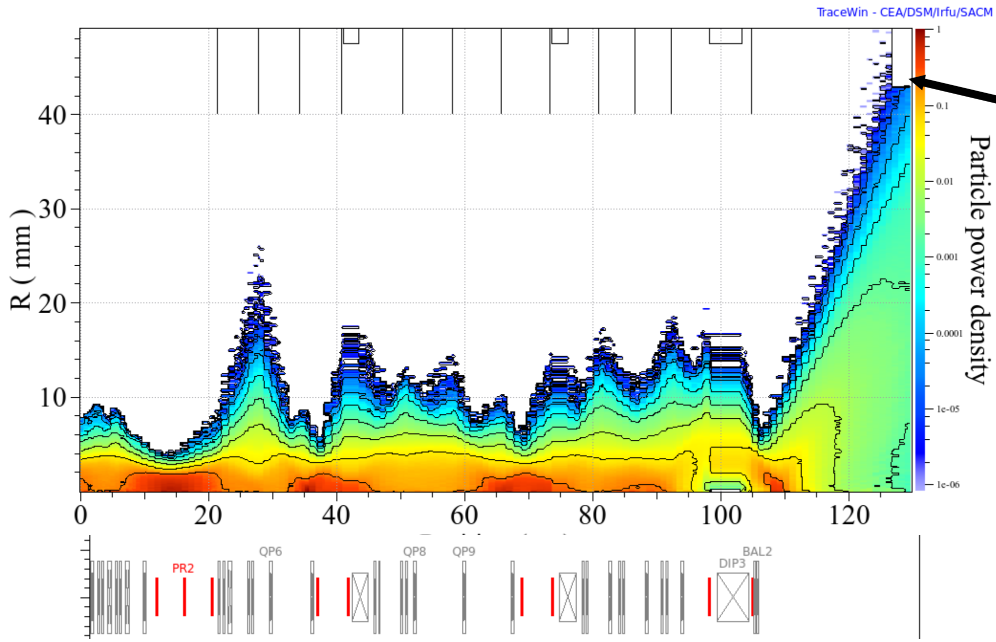
CDT project : beam line to reactor

Envelopes scanning specifications :

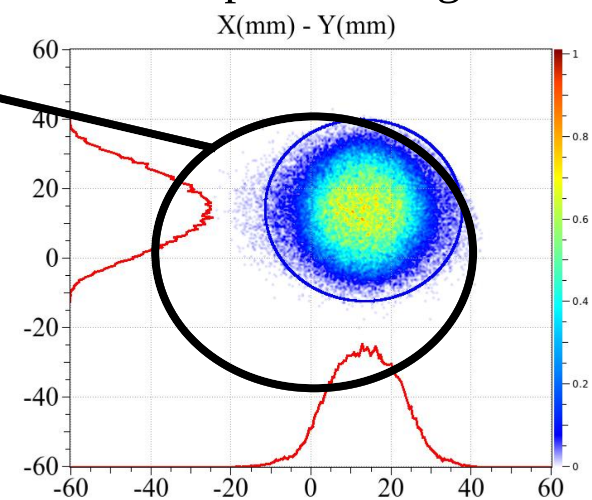
- Donut shape is impose by the Pb-Bi liquid target cooling
- Maximum beam scanning amplitude is fixed by target windows + last 2 meters beam pipe penetration inside the reactor core
- Scanning speed depend almost to target windows and Pb-Bi speed cooling

=> Need to 2 scanning dipoles located before the last 90° vertical dipole the maximum amplitude have to be less than 150G with frequency close to 100Hz (not yet frozen)

The scanning devices not yet design

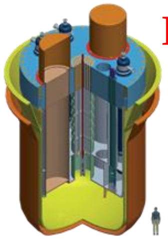


Footprint on target



13 kW beam loss on final tube

(over 2.4 MW total)



CDT project : beam line to reactor

Statistical error study

- **Static errors** are **randomly** applied to:
  - Magnets (displacement, field error)
  - Input beam (position, divergence, energy, emittance, intensity, mismatch)

- The **beam tuning procedure** is simulated step by step:
  - static errors are corrected when possible
  - errors on beam diagnostics measurements are taken into account

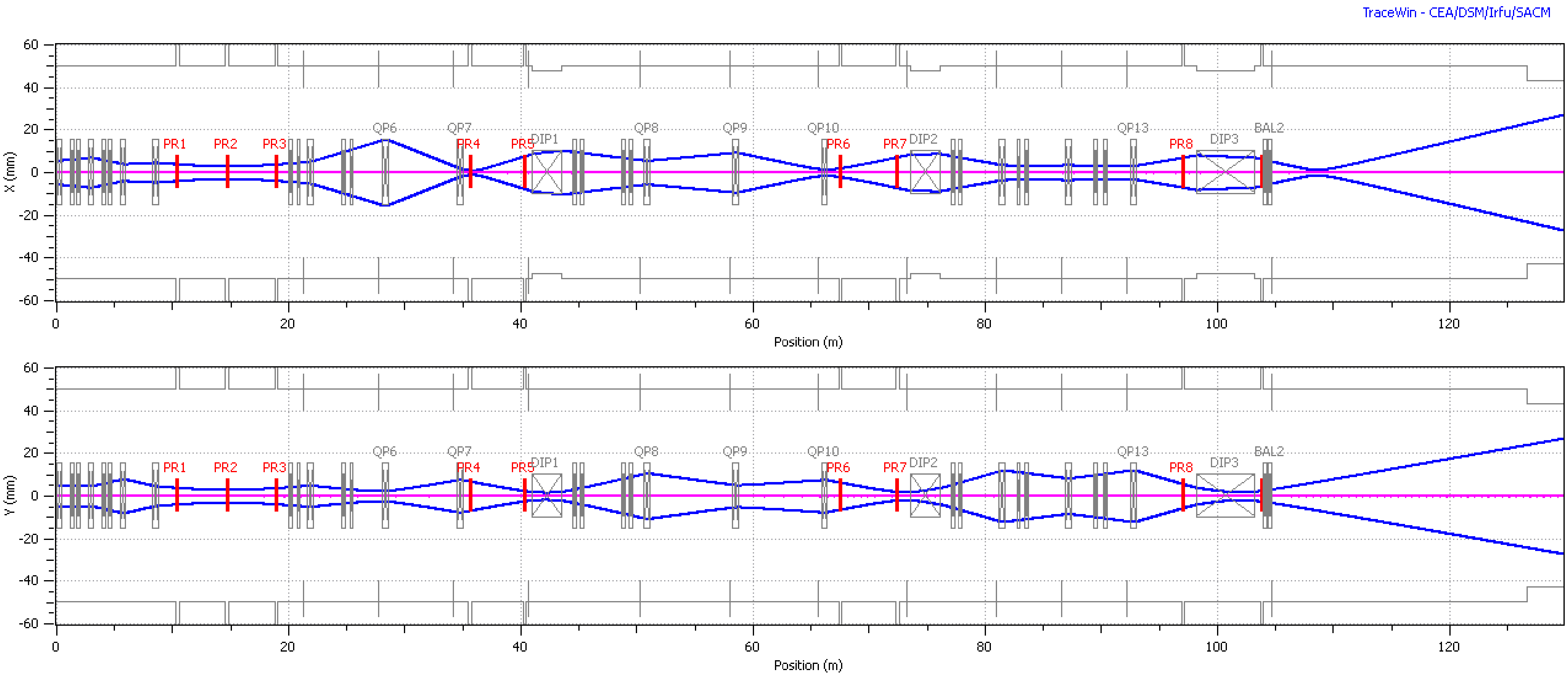
- **Dynamic errors** (mechanical vibrations, stability...) are then randomly applied:
  - These transient errors are not corrected
  - Applied to magnets (displacement, field error) & input beam (position, divergence, energy, emittance, intensity, mismatch)

- **Iteration** is performed to get good statistics:
  - X different cases (here 100)
  - each one with Y macro-particules (here 10^5)

CDT project : beam line to reactor

Error calculations

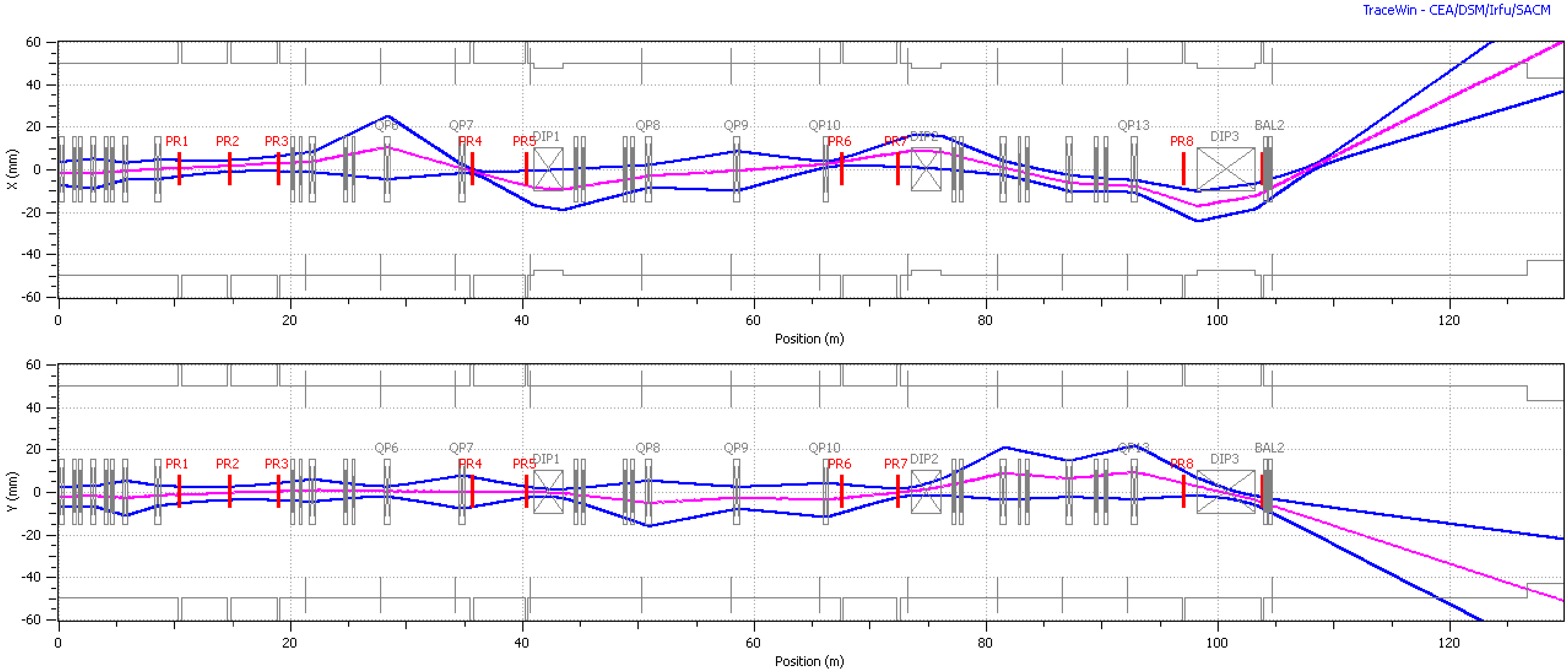
1. Nominal 99% envelopes without errors, without scanning



CDT project : beam line to reactor

Error calculations

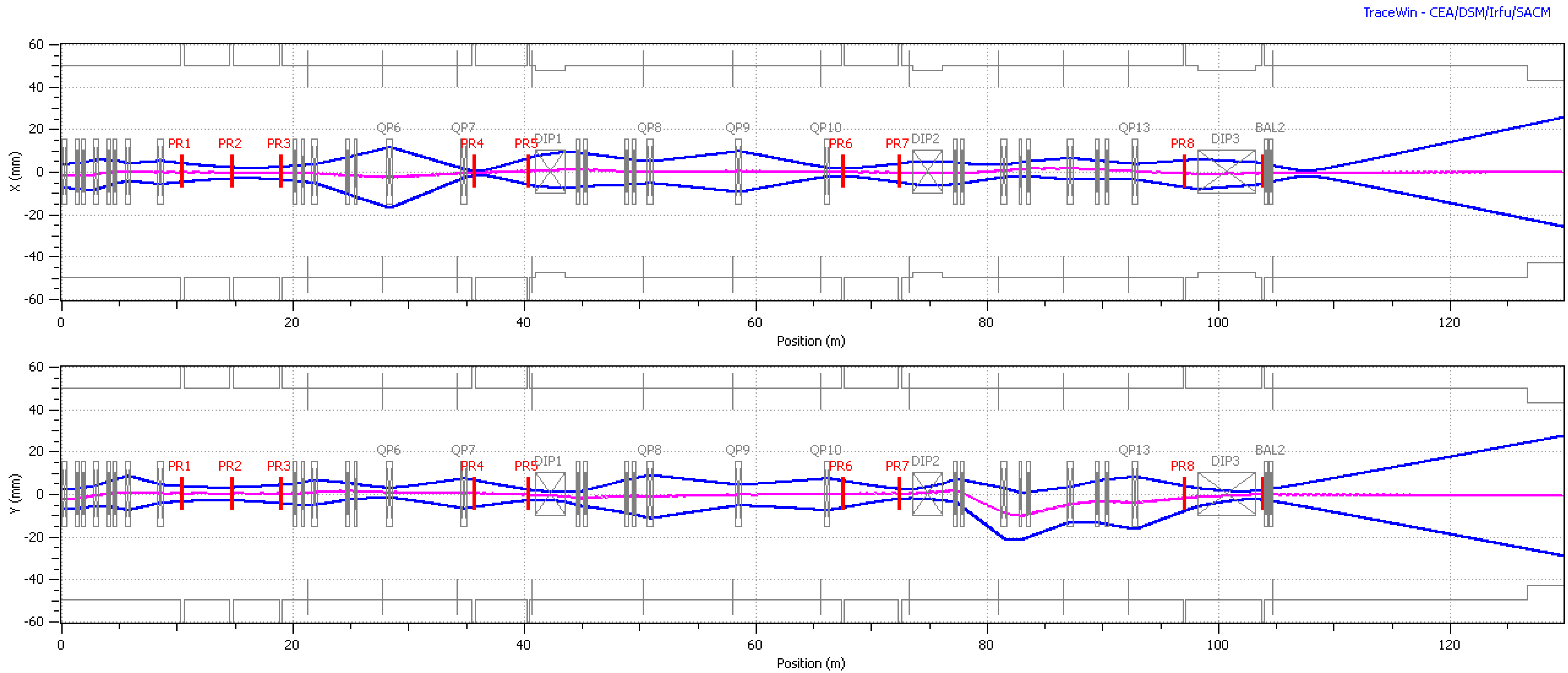
2. 99% envelopes with UNCORRECTED static errors (random distribution) , without scanning



CDT project : beam line to reactor

Error calculations

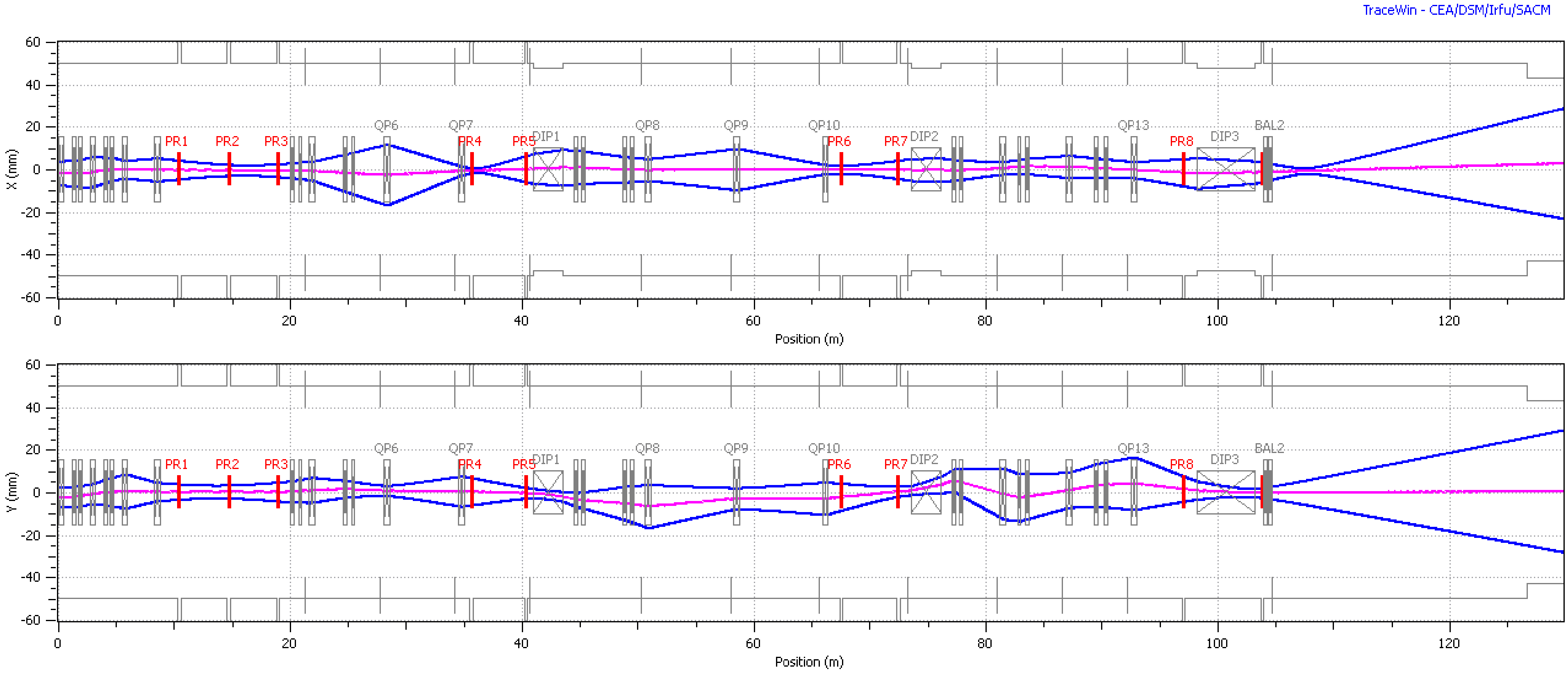
3. 99% envelopes with CORRECTED static errors (same random distribution) , without scanning



CDT project : beam line to reactor

Error calculations

4. 99% envelopes with CORRECTED static errors + uncorrected dynamic errors, without scanning



CDT project : beam line to reactor

Error calculations: beam losses

Possible losses on collimator:

- Min = 0, Max = 29kW

- Mean = 0.3 kW, RMS = 3kW

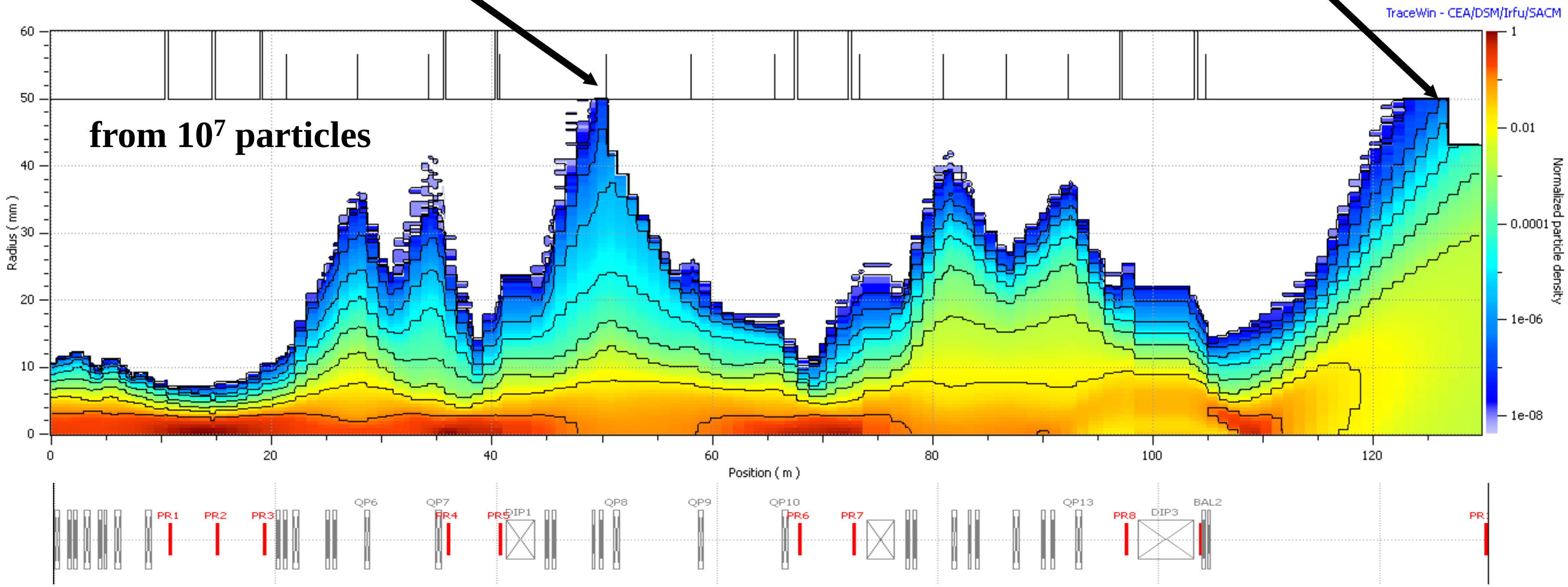
=> Losses in 1% cases

Losses on final tube:

- Min = 0.5kW, Max = 110kW

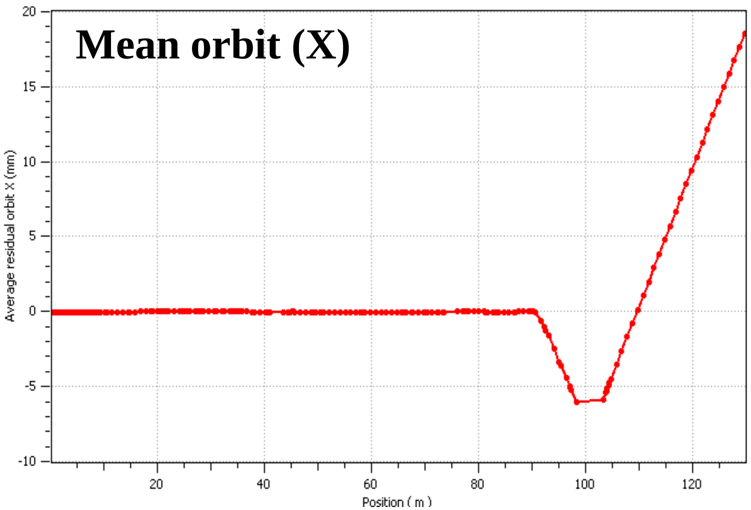
- Mean = 15 kW, RMS = 14kW

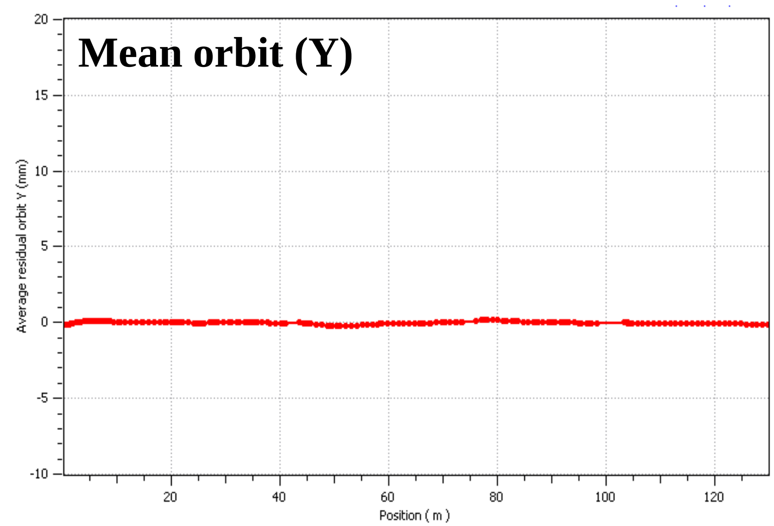
from 10^7 particles

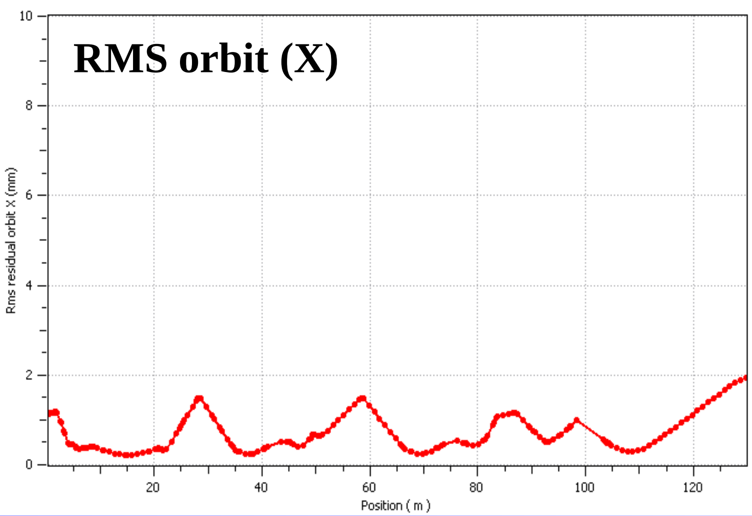


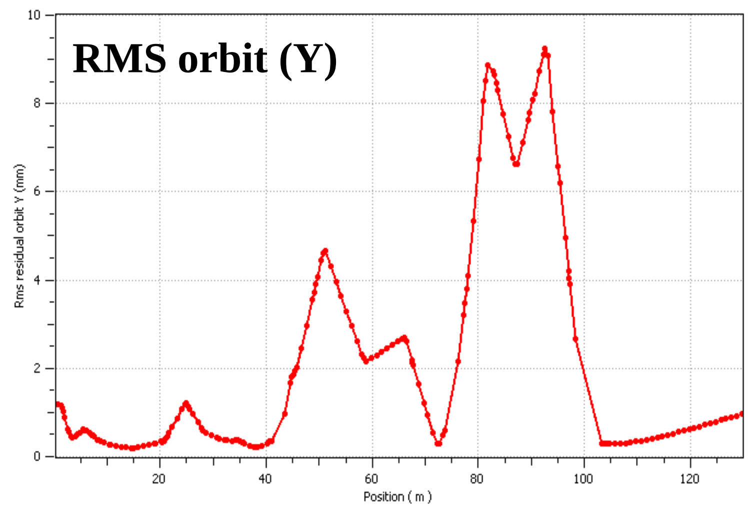
CDT project : beam line to reactor

Error calculations: trajectories



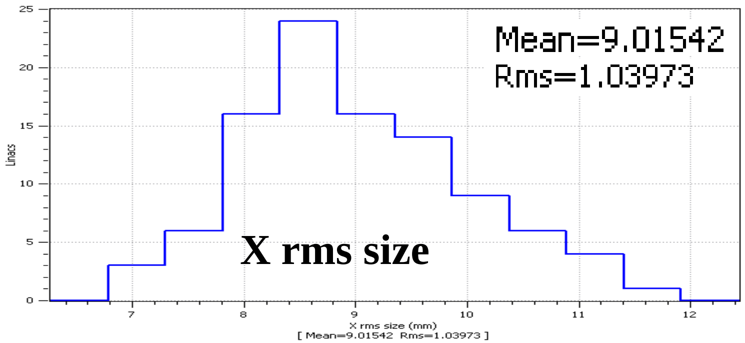


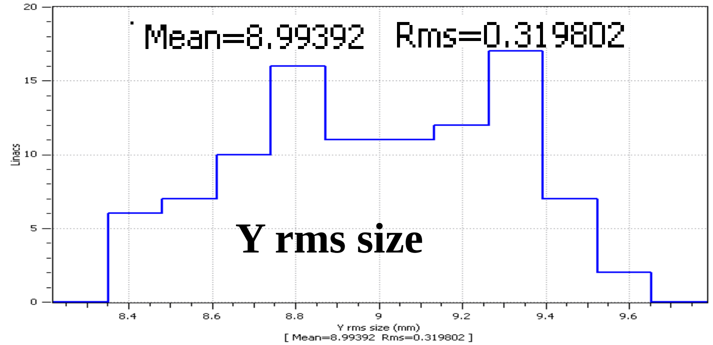


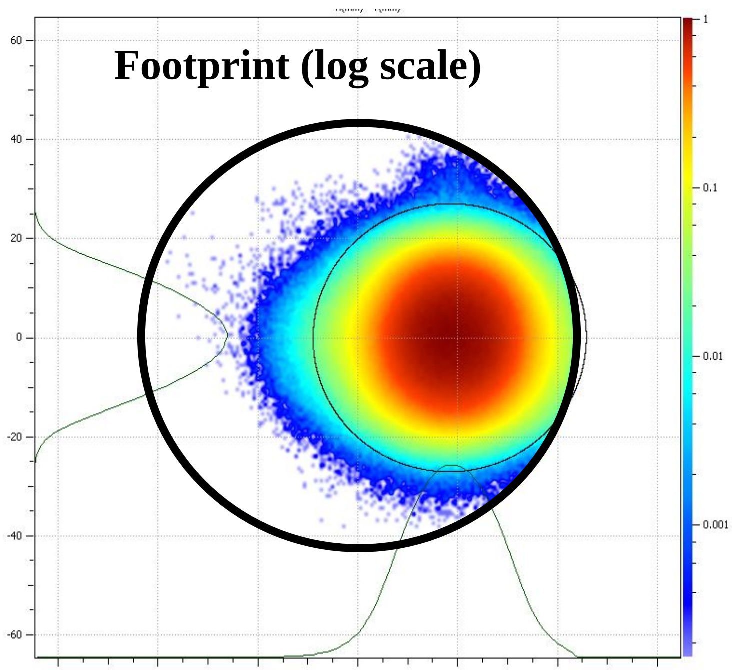


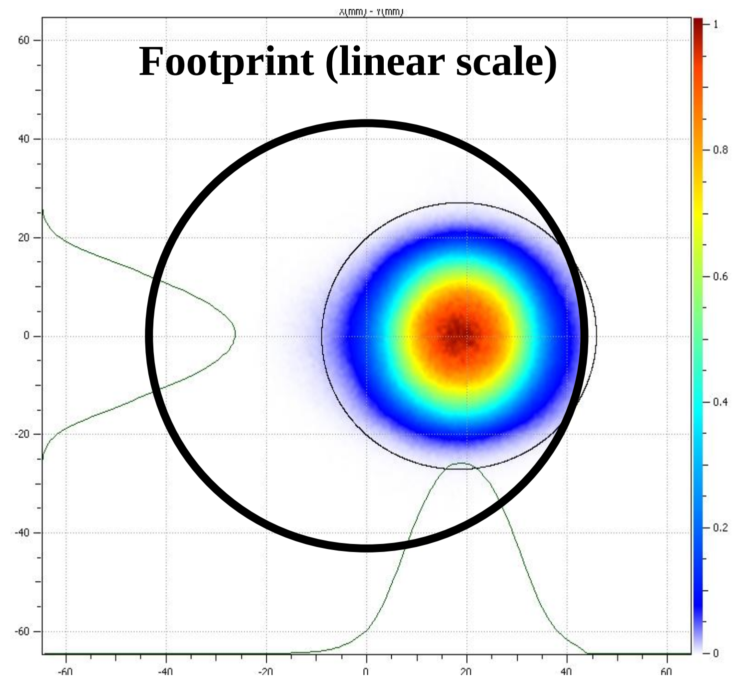
CDT project : beam line to reactor

Error calculations: target footprint









CDT project : beam line to reactor

Error calculations: sensitivity

- Errors impacting the **orbit excursion** through the line (i.e. beam losses)
    1. Beam energy jitter: ±1MeV => 5 mm rms deviation (DYNAMIC)
    2. BPM precision: ±0.5mm => 2 mm rms deviation (STATIC)
    3. Magnets alignement: ±0.3mm => 1 mm rms deviation (STATIC)
    4. Dipole field stability: $\pm 2.10^{-5}$ => 0.5mm rms deviation (DYNAMIC)

- Errors impacting the **position on target**
    1. Input beam divergence jitter: ±0.01mrad => 0.7mm rms (DYNAMIC)
    2. Input beam position jitter: ±0.1mm => 0.6mm rms (DYNAMIC)
    3. Dipole field stability: $\pm 2.10^{-5}$ => 0.5mm rms (DYNAMIC)
    4. Quadrupoles mechanical vibrations: ±10µm => 0.4mm rms (DYNAMIC)
    5. Beam energy jitter: ±1MeV => 0.3mm rms deviation (DYNAMIC)
    6. Dipole mechanical vibration (Y): ±10µm => 0.2mm rms (DYNAMIC)

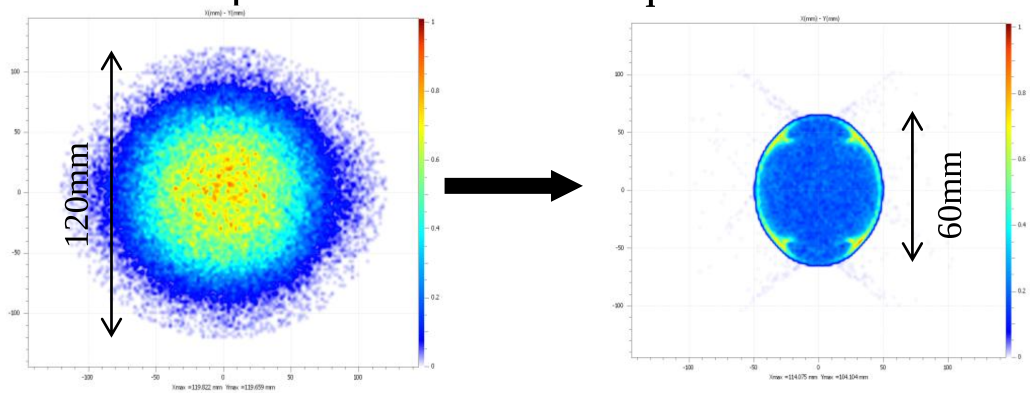
- Errors impacting the spot **size on target**
    1. Quadrupoles gradient stability: $\pm 10^{-3}$ => 0.15mm rms (DYNAMIC)
    2. Beam energy jitter: ±1MeV => 0.1mm rms (DYNAMIC)
    3. Beam profiler precision measurement: ±0.5mm => 0.1mm rms (STATIC)

CDT project : beam line to reactor

Multipole beam expander ?

Homogeneous beam density distribution can also be performed using a set of **octupole magnets** in front of the target:

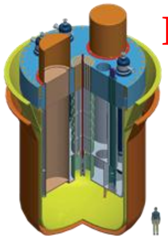
- The first set of octupoles (1 or 2) produces a square homogeneous footprint
- An additional turned octupole transforms the square in circle



This is a beautiful solution, but several drawbacks:

- Produces a lot of beam halo => has to be located near the final target
  1. Impossible in our case
  2. Tested location: upstream. Unmanageable (unless a possible 2^{nd} order O-I system ...?)
- Extremely sensitive to any beam misalignment or beam size variation

=> For MYRRHA, it seems **extremely complicated (if not impossible)** to implement

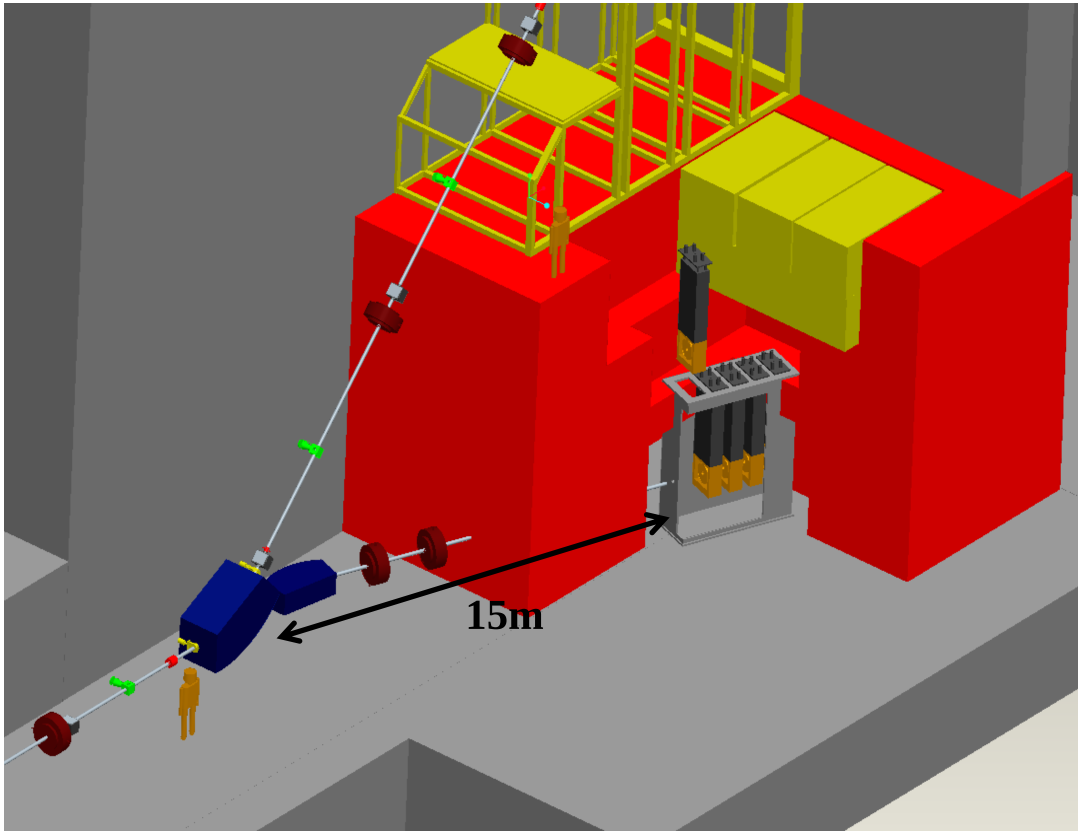


MYRRHA / CDT

CDT project : beam line to reactor

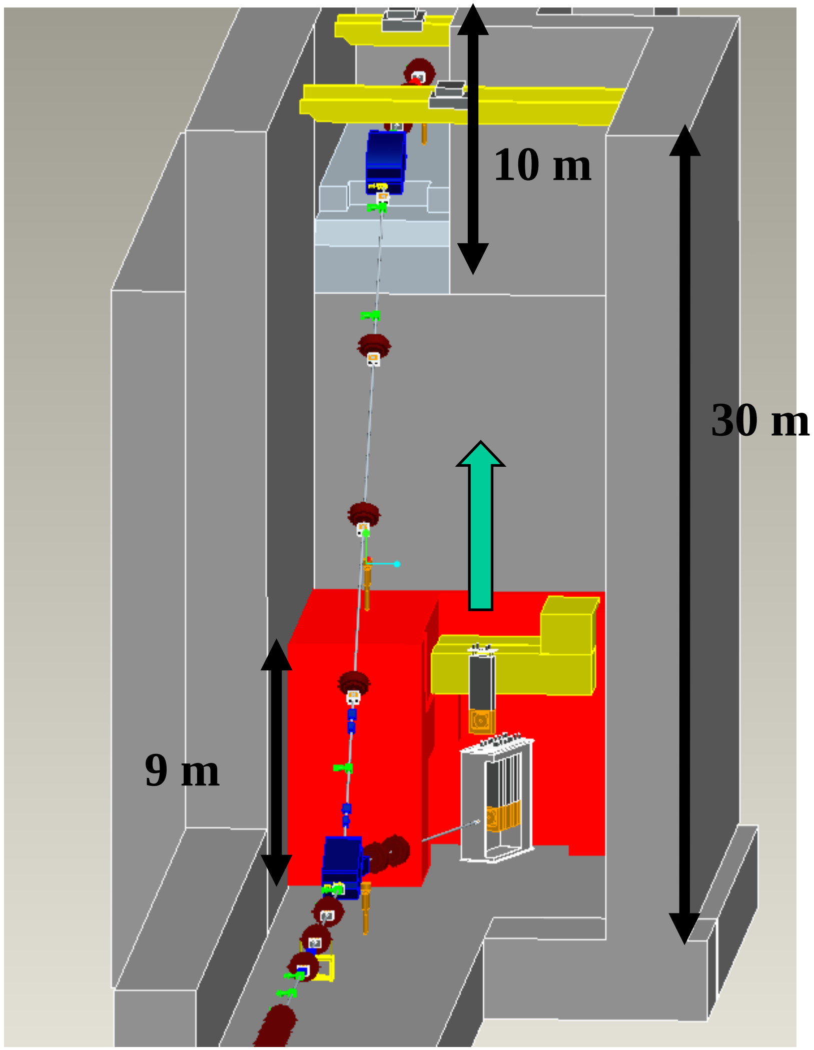
Beam line to dump

- Present layout of the line:
  - 20° dipole to avoid neutron back streaming & ease the maintenance
  - 2 quadrupoles to defocus beam on dump
- Beam dump design
  - Preliminary design from the 1 MW PSI proton dump (larger)
  - Required shielding, preliminary study performed
  - Detailed mechanical & thermal assessments to be done



CDT project : beam line to reactor

Beam line to dump



Beam Dump is handled from the top using the Common crane (cf PSI).

Due to the 20° deviation. It is not necessary to dismount the line.

The space for a specific closed beam dump bunker with its own crane is enough.

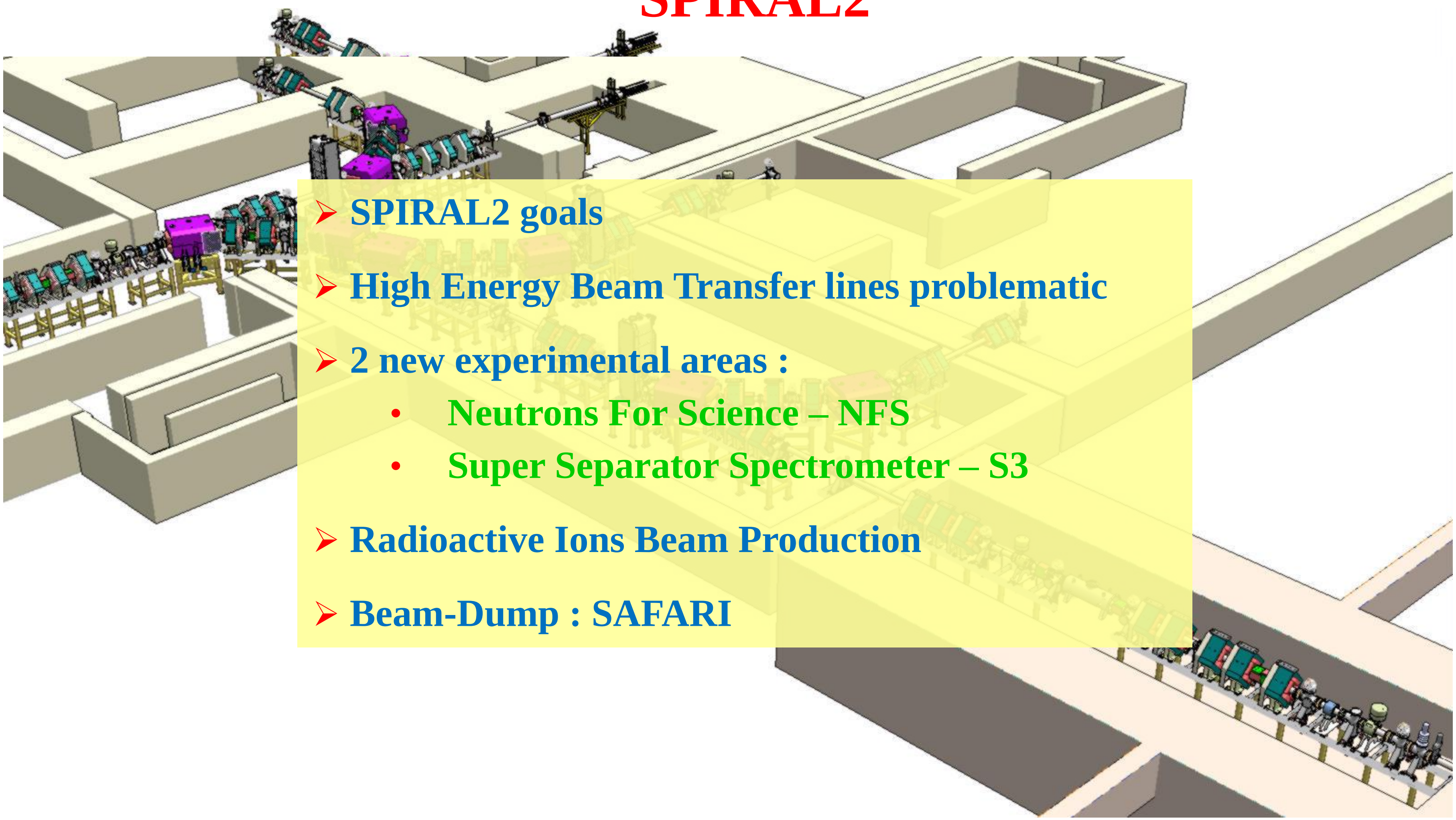
Cost will be evaluated in the details design sutdy to MYRRHA

Conclusions

CDT project : beam line to reactor

- Consolidated design of the beam line to reactor achieved
- AC steering magnets are preferred
- Error study shows very robust behavior (sensitivity in the X-plane may be optimised)
- Up to 50 kW beam losses have to be considered along the reactor beam tube
- Beam dump design on-going, need to be study in details (structure, safety …)

High Energy Beam Transport Lines for SPIRAL2



- SPIRAL2 goals
- High Energy Beam Transfer lines problematic
- 2 new experimental areas :
  - Neutrons For Science – NFS
  - Super Separator Spectrometer – S3
- Radioactive Ions Beam Production
- Beam-Dump : SAFARI

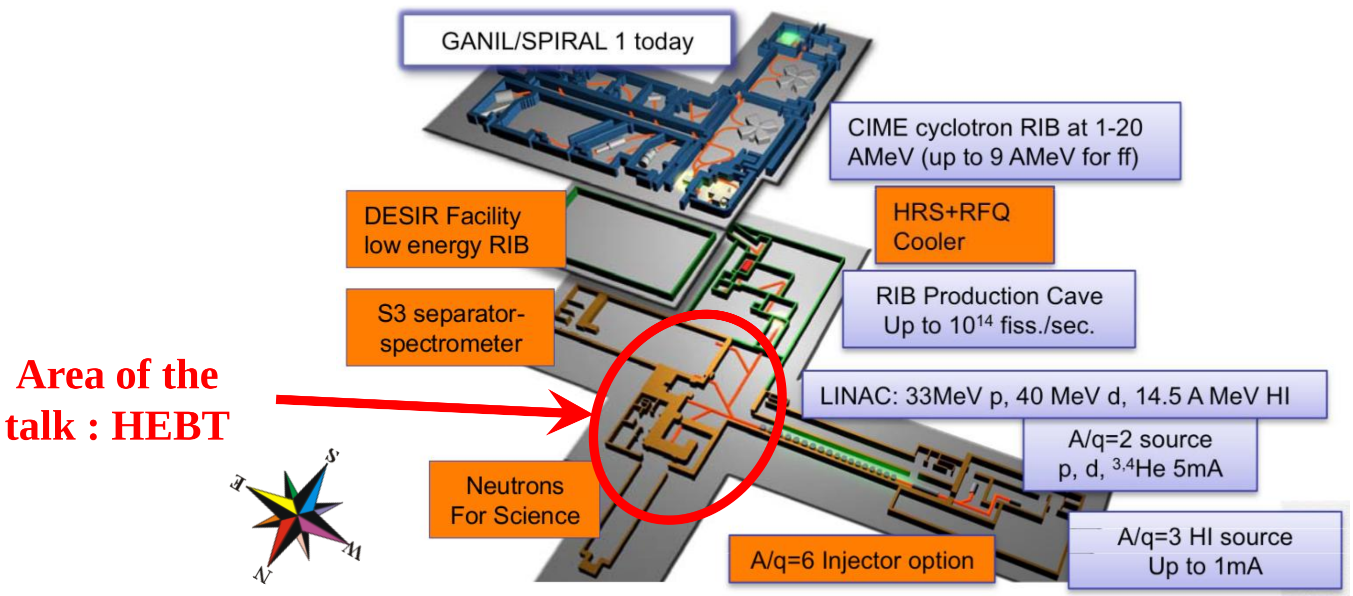
L. Perrot : perrot@ipno.in2p3.fr , CNRS-IN2P3-IPNO

SPIRAL2 goals

- Strong demand on Radioactive Ions Beams by the nuclear physics community
- Fundamental knowledge of the atomic nuclei
- Interdisciplinary research : ions-ions collisions, neutrons XS, material irradiations using neutrons

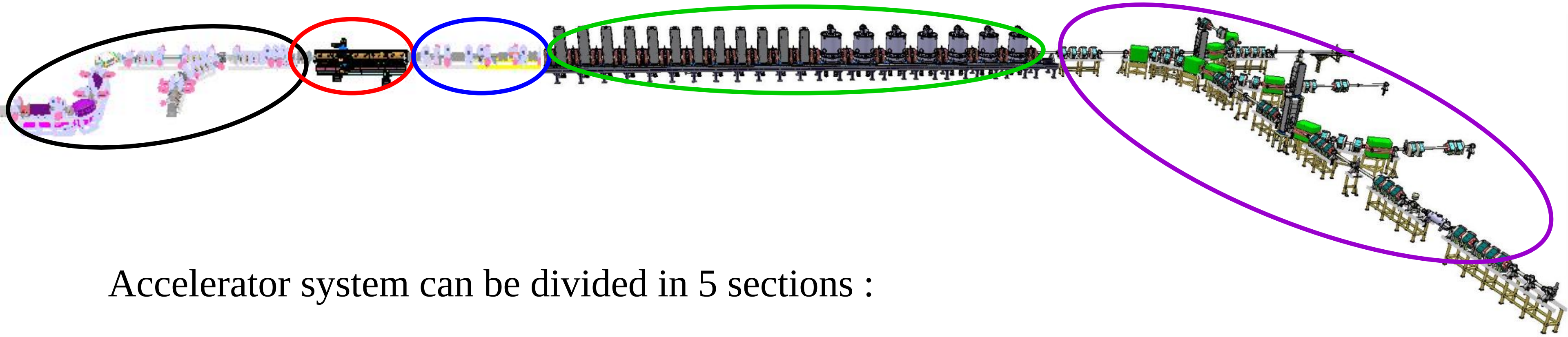
Extend the actual possibilities given by GANIL at Caen

- RI produced by fission process, fusion evaporation residues or transfer products
- High intensity stable primary beams : P, D, ^{3,4}He, heavy ions with A/Q=3 (1mA-5mA)
- Energy range : from 2MeV/u up to 20MeV/u (D), 14.5MeV/u (HI), 33MeV (P)



Summarize about the accelerator

SPIRAL2 : a new underground accelerator (-9.5m)



Accelerator system can be divided in 5 sections :

- **LBE1&2** (Low energy) : D,P & A/Q=3 ECR sources + selection + transfer line, E_d~40keV, 32m
- **RFQ** : from 40keV up to 1.46MeV for Deuterons, f=88.0525MHz, 5m
- **MEBT** (intermediate energy) : future 1/6 ions line connection, fast chopper, 8.1m
- **LINAC** : 2 cavity series: β=0.07 & 0.12, 29.5m length
- **HEBT** : High Energy Beam Transport (this presentation)

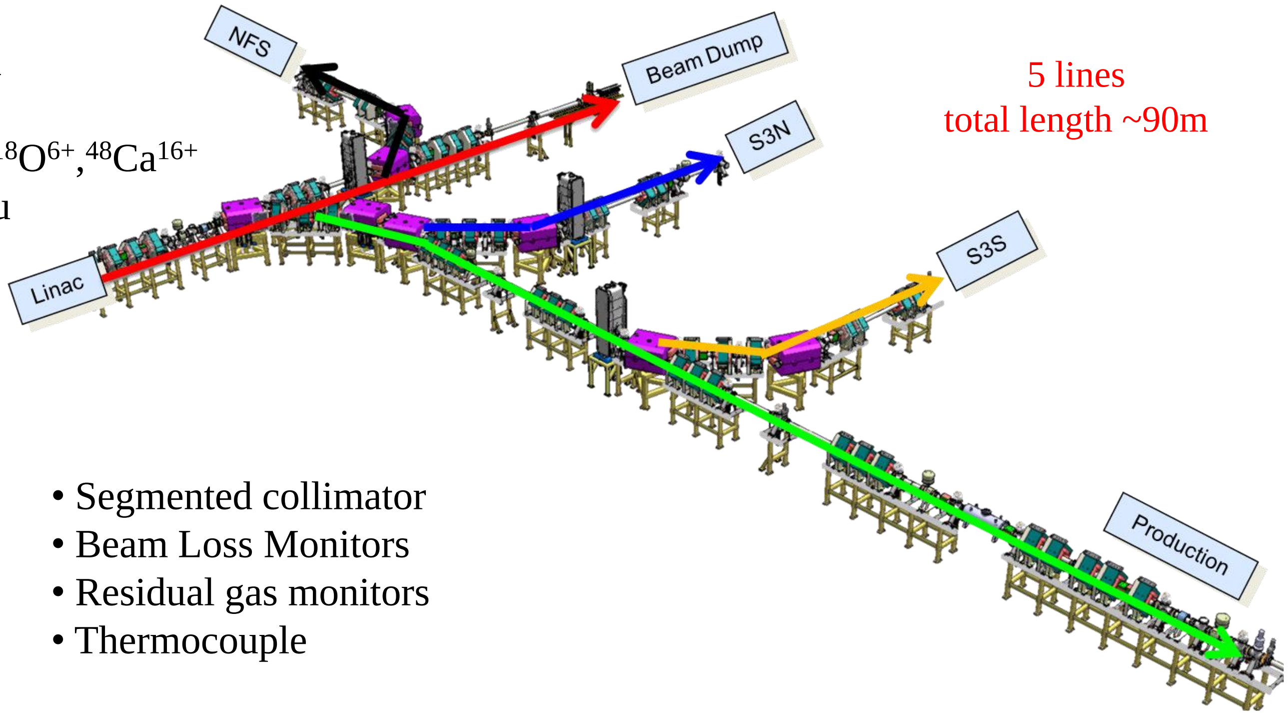
High Energy Beam Transport lines

- Interface between accelerator and exp. areas or RIB factory via target and/or converter
- Close to the physics experiments (NFS, S3)
- HEBT must be able to transport the large range of species at various energies
- Beam losses have to be minimized: < 1 W/m

Constraints : Sizes of the quad, dipoles, i.e. available place.
Current alimentation stability specifications. Diagnostics working range.

Deuterons : 4MeV – 40MeV, 5mA
Protons : 2MeV – 33MeV, 5mA
Ions A/Q=3 : 2-14.5MeV/u, 1mA $^{18}O^{6+}$,$^{48}Ca^{16+}$
Upgrade : A/Q=6 : up to 8.5MeV/u

=> $0.2Tm < B\rho < 2.52Tm$



5 lines
total length ~90m

Instrumentation :

- Beam profiler
- ToF pick-up for beam energy
- Current : ACCT/DCCT
- Beam Position Monitors
- Loss rings
- Segmented collimator
- Beam Loss Monitors
- Residual gas monitors
- Thermocouple

NFS : Neutrons For Science

New experimental area : Fission process, nuclear waste transmutation, future fission & fusion reactors

use the n-ToF or activation technique

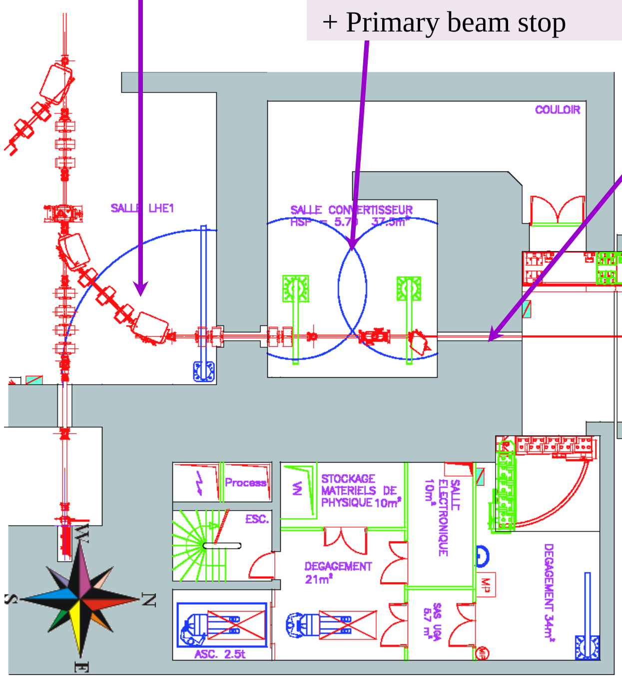
- XS measurements
- Atomic physics : material under irradiation, damage

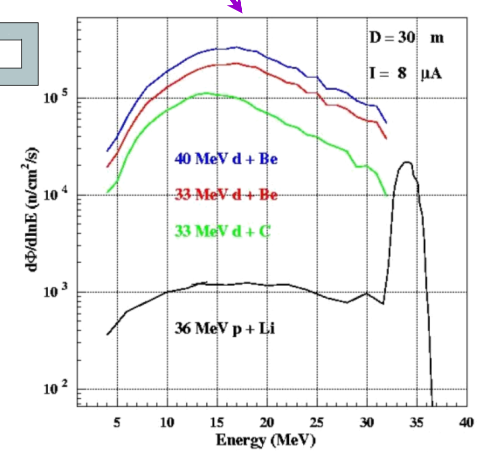
HEBT-NFS
Beam : D, P, He, C
Imax=50µA, P=2kW

Converter room : 6m long
Need to a versatile targets chamber
Targets : Be, C, Li, Al, Fe, Cu, SiC, ZrO_2
+Dipole for Proton beam rejection
+ Primary beam stop

Neutrons Collimator
ϕ=20mm

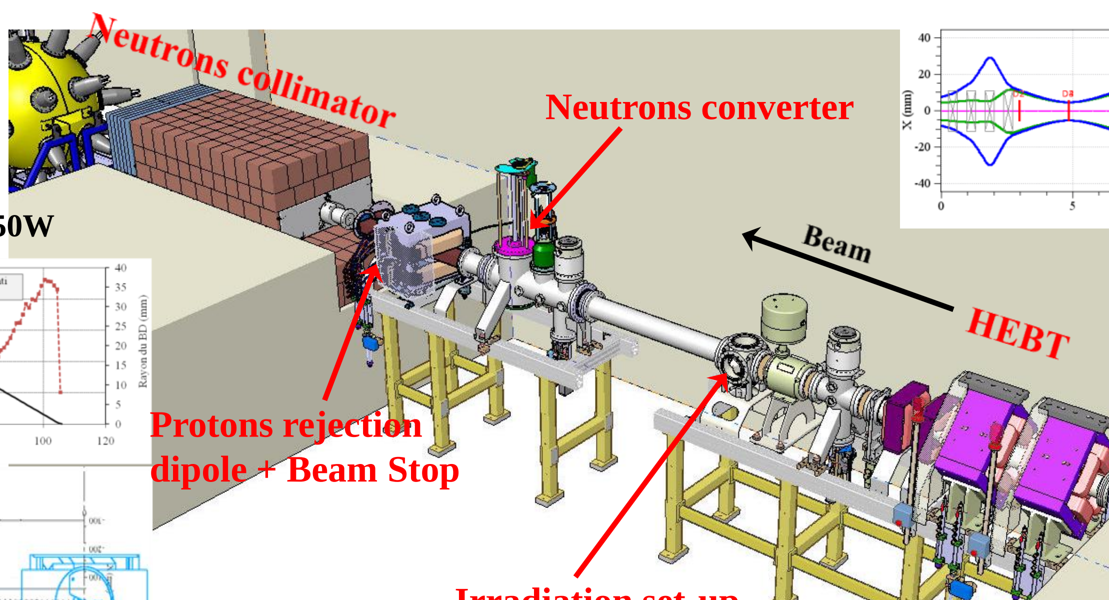
Neutrons Time of Flight room : 25m long
Various detectors location surrounded targets like actinides (Pu, Cm …)
Path converter to detector : neutrons flux / neutrons resolution
+Neutrons beam-dump

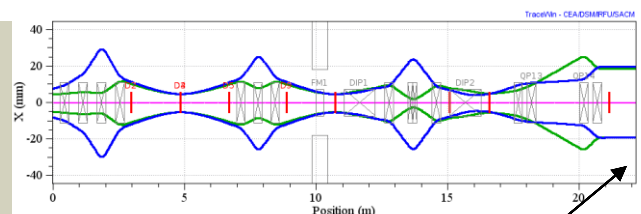




NFS : Neutrons For Science

- Primary beam working range : 0.4Tm<Bρ<1.3Tm with light nuclides (D up to 40MeV, P up to 33MeV)
- P_{max}=2kW : Deuterons at 40MeV, 50µA using current reduction with slow chopper (irradiation) or fast chopper / bunch suppressor up to 1/100 (n-ToF)
- Sizes on irradiation targets and n-converter : from 1mm up to 4mm RMS
- 1ns bunch time length required only for n-ToF experiments (D or P beam)
- All primaries beam are stopped in target except P-beam on thin Li target. Need rejection dipole + dump

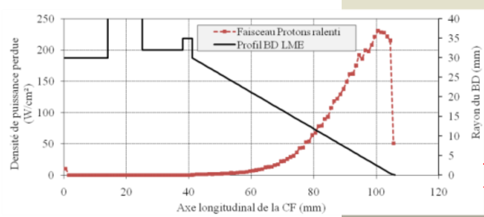


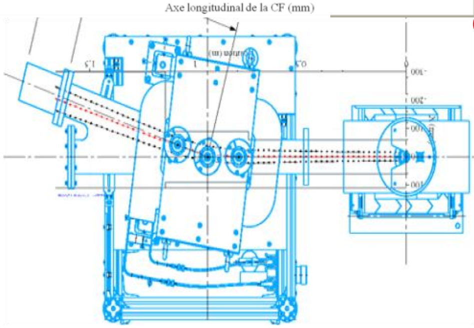


Beam size=40mm

For ±5RMS

Protons BS P_{max}=1650W





S3 : Super Separator Spectrometer

A new experimental area dedicated to :

- Super-heavy & very-heavy nuclei : $Z > 100$
- Spectroscopy at and beyond the drip-line
- Isomers and ground state properties
- Multi-nucleon transfer and deep inelastic reactions

Requiring the separation of very rare event from intense backgrounds : S3

LHE-S3

Beams : A/Q=3, ^{18}O, ^{48}Ca, ^{58}Ni, ^{12}C, ^{86}Kr

Imax=1mA, 2MeV/u – 14.5MeV/u

S3 targets

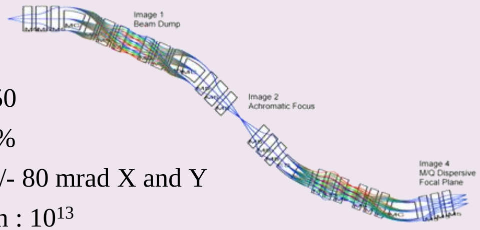
U, Am, Cm, Ti

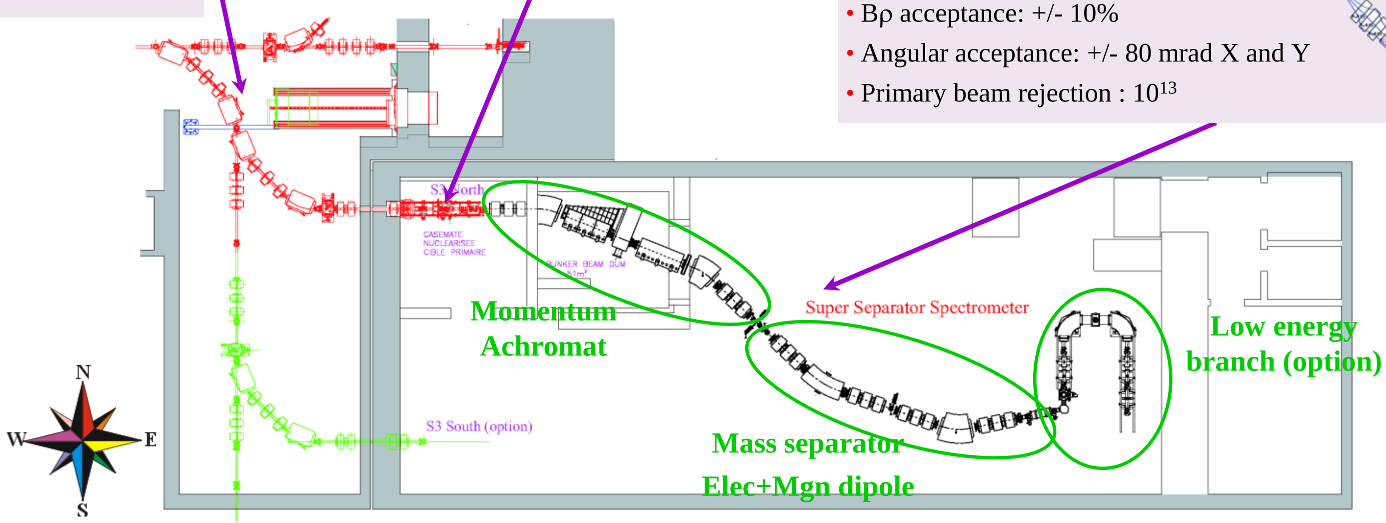
Rotated system

+ beam sweeper

A Challenging Separator + Spectrometer. Based on J. Nolen design

- $B\rho_{max}$ = 2Tm
- $E\rho_{max}$ = 10 MV
- Mass resolution = 1/350
- $B\rho$ acceptance: +/- 10%
- Angular acceptance: +/- 80 mrad X and Y
- Primary beam rejection : 10^{13}

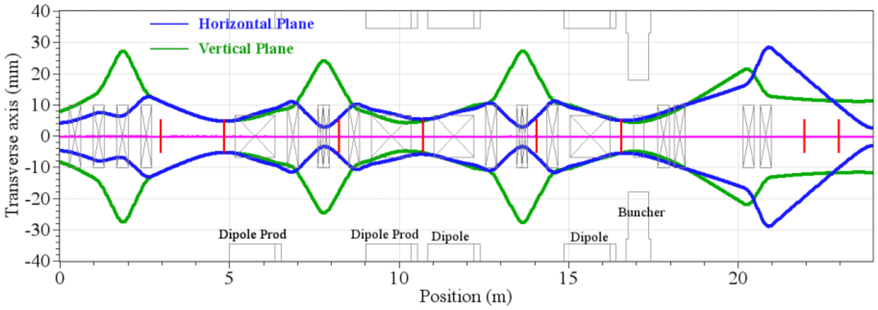




Proposition for the First Day Experiment : $^{40\text{-}48}Ca + ^{238}U \rightarrow ^{278\text{-}286}112^*$

S3 : Super Separator Spectrometer

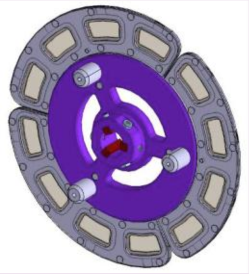
- Primary beam working range : 0.6Tm<Bρ<1.65Tm with ions to A/Q=3
- Beam sizes on target : RMS X=0.5mm, RMS Y : from 0.5 up to 2.5mm
- Careful and safe primary beam and S3 tuning (profiles, energy, current) have to be obtain



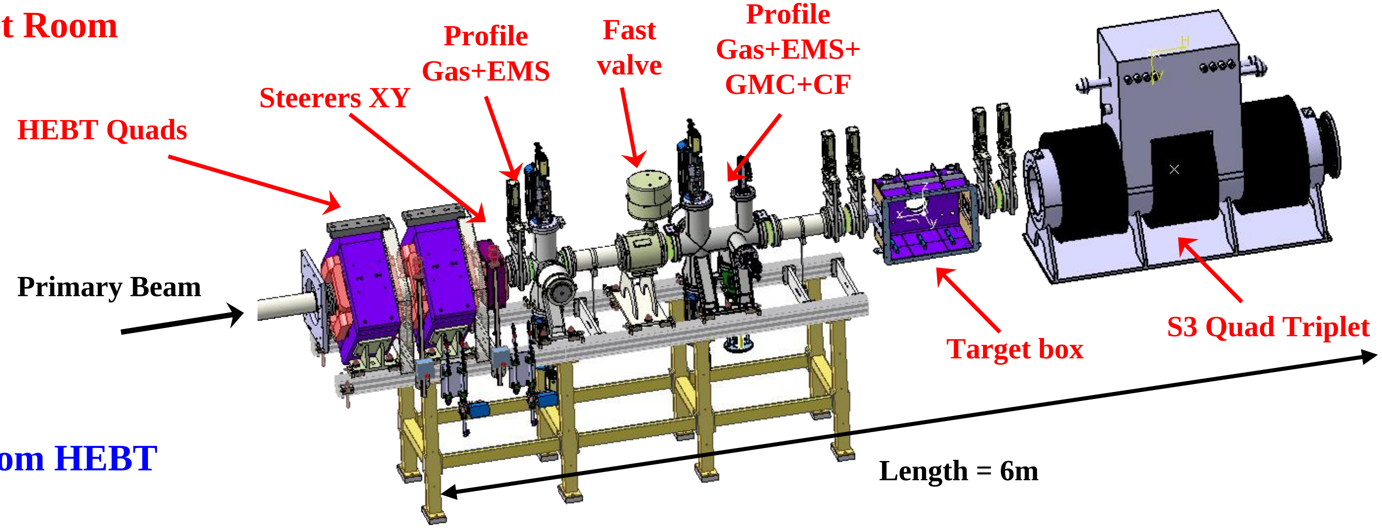
High Power Target Stations

2 rotating targets types are studies :

- Stables : ^{208}Pb, ^{209}Bi, Ni, Ca, C
  with Radius = 25cm
- Actinides : ^{232}Th, ^{238}U, $^{239-242-244}$Pu, ^{248}Cm
  with Radius=6-15cm



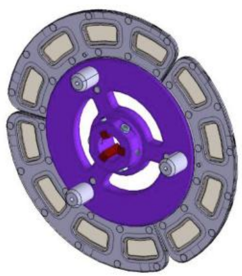
S3 target Room

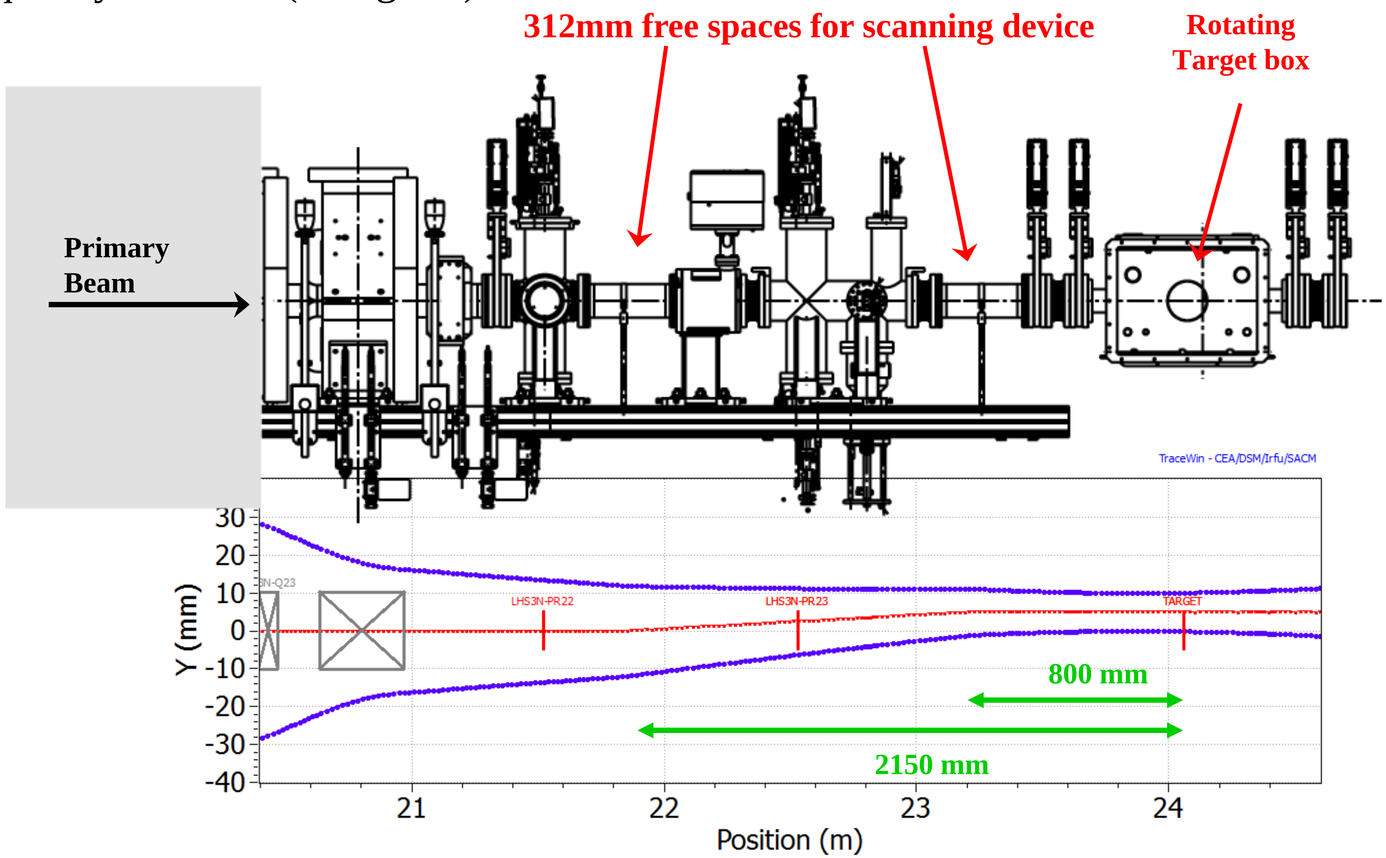


S3 : Super Separator Spectrometer

For specific cases the beam power density deposed on target imposed a beam sweeping

- 2 free space location along the last drift space, pipe diameter=120mm
- Suppress the additional angle contribution for the secondary beam
- Only on vertical plane Δy=10mm. Not useful on horizontal plane
- B_{max}<0.2kG or E_{max}<60kV for Bρ=1.65Tm / Eρ=86.21MV
- Frequency ~10 kHz (triangular)





Technical solution not yet defined

HEBT up to Radioactive Ions Area

Radioactive Ions Beams : Production to new isotopes

- To Perform experiments on a wide range of rich Nuclei far from the line of stability
- Different production mechanisms and techniques to create the beams

Target R&D and RIB production module is particularly challenging

- Objective is to have a UCx target which will be able to receive the 200kW Deuterons Beam
- Fission rate inside target expected : 10^{14} fission/s
- Produced Nuclei : 60<A<140, rate : from 10^{6} up to 10^{11} pps

HEBT-Prod RIB

Beams : D, light ions ^{3,4}He

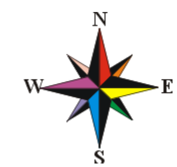
Imax=5mA

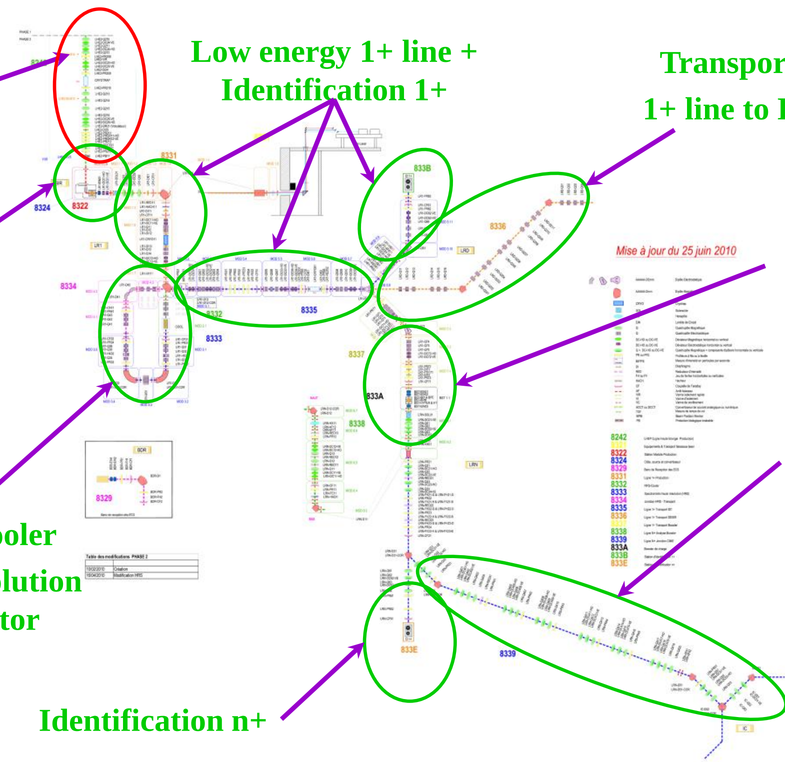
Energy : 40MeV, 14.5MeV/u

Line Length from LINAC=45m

Low energy 1+ line + Identification 1+

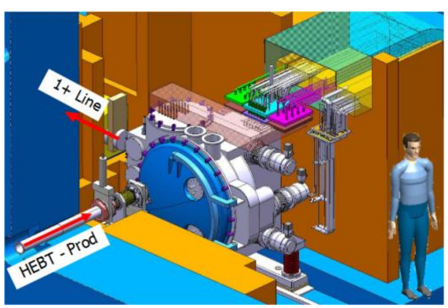
Transport Connection 1+ line to DESIR (100m)





Charge Booster + Analyses

Production module



RFQ-Cooler

High Resolution Separator

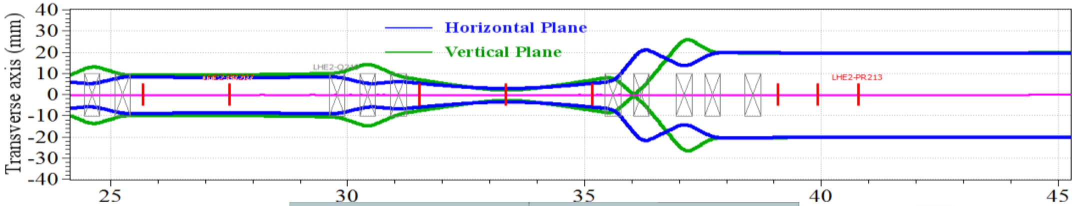
N+ line up to CIME cyclotron and existing GANIL lines

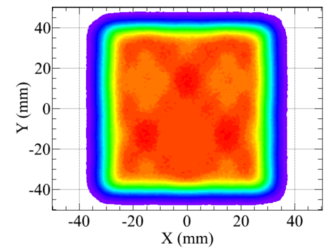
Identification n+

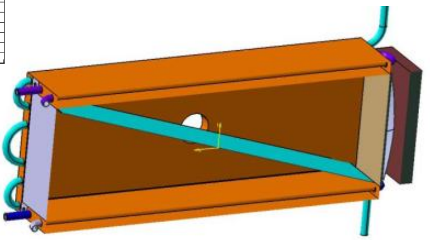
HEBT up to Radioactive Ions Area

Beam specifications:
- No constraints on beam pulsation or bunch length
- 3 sizes requirements:
  - UCx target for FF production : 40MeV Deuterons, 3.4mm (50kW) et 6.7mm (200kW) RMS, stability ±1mm
  - Fusion evaporation with ions A/Q=3 at 5MeV/u : 2.2±0.5mm RMS, stability ±0.6mm
  - Other beams, others targets : 60x80mm² spot on 13° target angle. Need a beam scanning in X & Y.

    Sweeper specification are : L_m=330mm, F_X=251 Hz and B_X=346G, F_Y=186 Hz and B_Y=462G

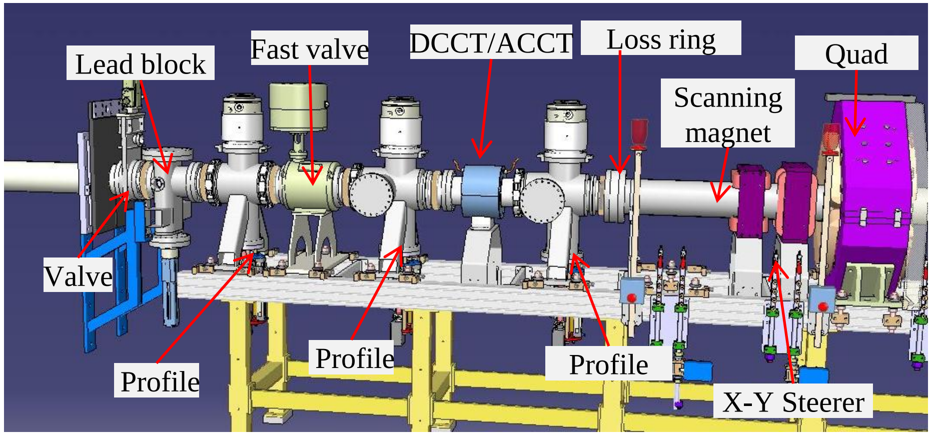






- Careful attention to beam tuning procedure (P=200kW)
- Important effort to be focused on the last matching section for beam control, safety aspects …
- Area access will not be easy (interface with prod. building)

The ultimate part is not yet completely finalized

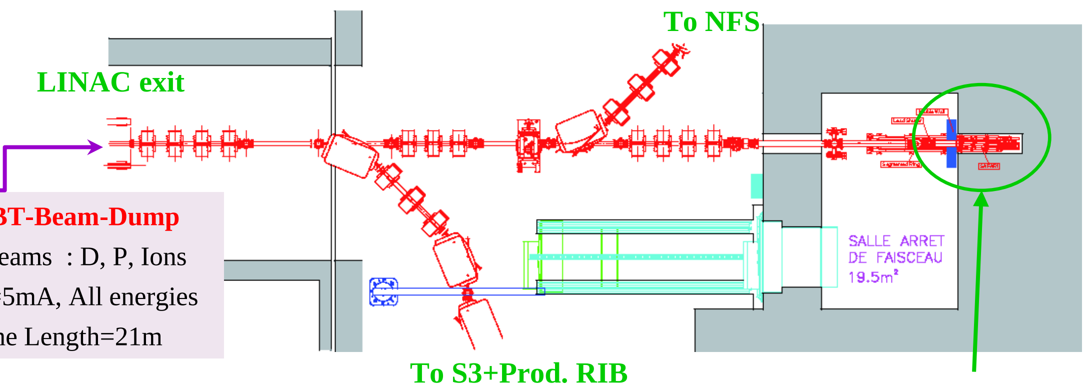


Beam-dump : SAFARI

SAFARI : Système d'Arrêt Faisceau Adapté aux Rayons Intenses

Optimized Beam Stop Device for High Intensity Beams

- Accelerator facility commissioning
- Beam tuning along the accelerator
- Beam qualifications and controls during run



HEBT-Beam-Dump

All beams : D, P, Ions

Imax=5mA, All energies

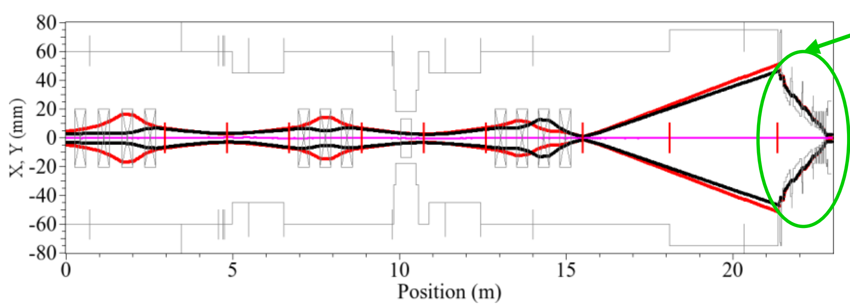
Line Length=21m

Must be able to stop a Deuterons beam at 40MeV and 5mA (200kW)

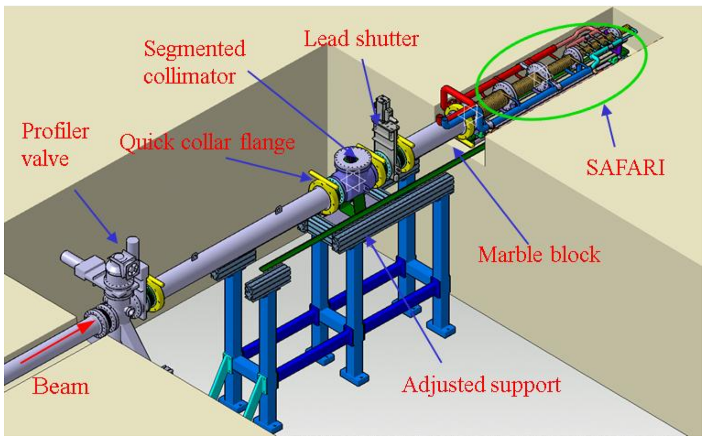
Safety :

- A separated cave for the device, restricted area. No access in normal operation
- Limitations is 10kW during 1 hour / day for a 3 months run (3'/day @ 200kW)

=> Dose rate = 20mSv/h at 20cm after 1 day



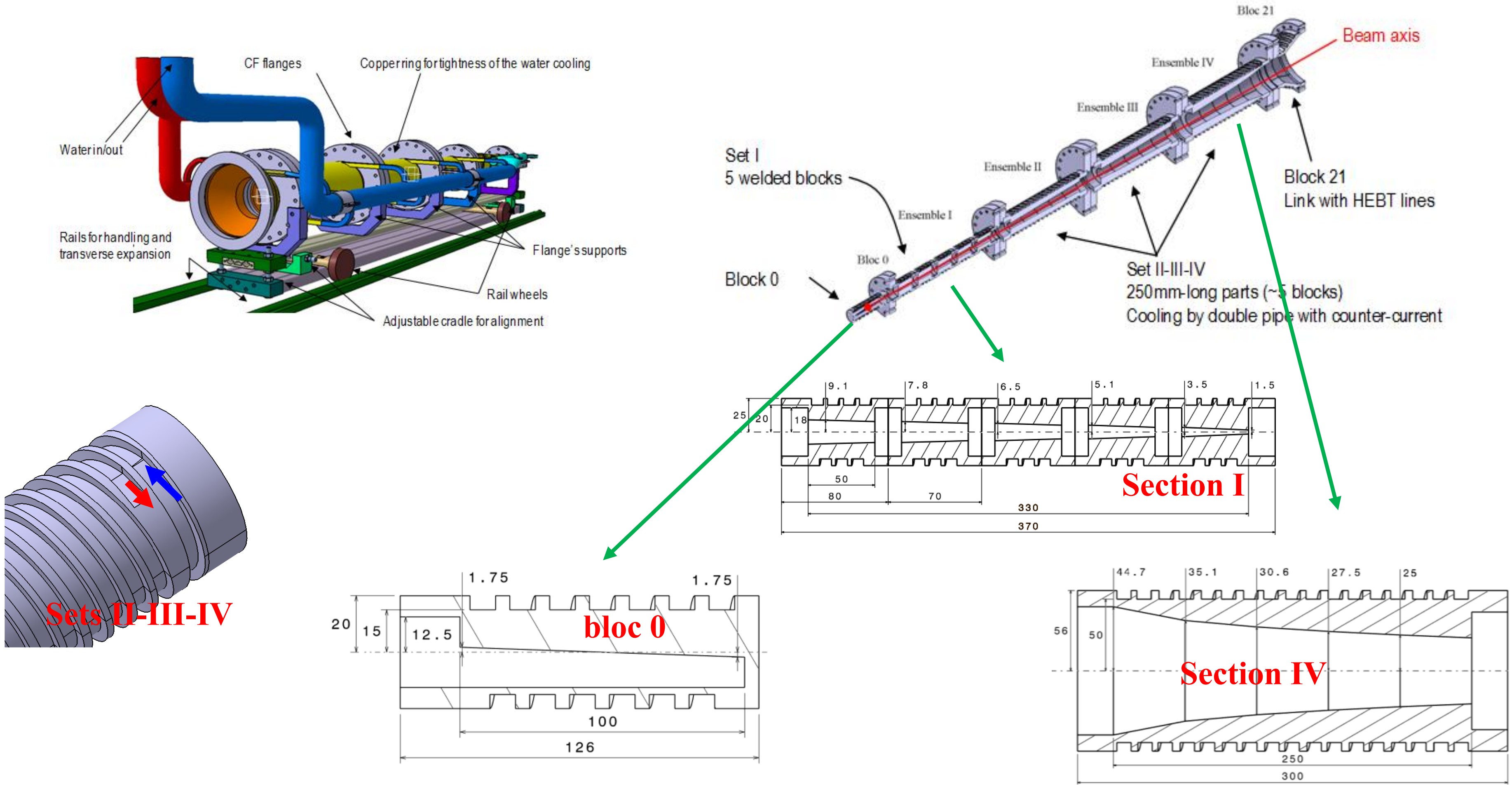
All beam type matched in order to have a RMSx,y~16mm at the beam-dump entrance



Beam-dump : SAFARI

BS Structure : Length = 1609mm, various design studies since 2007 and iterative process (thermal, mechanical, beam optics…)

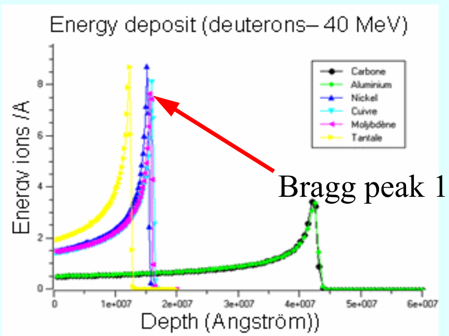
- 6 Copper sections (Cu OFHC, without Oxygen) with CF flanges in between, reduced vacuum volume
- Internal radius see by beam particles decreases progressively from r_{max}=48mm (3σ)
- Cooling system for sections II à IV : water channels with counter-flow double loop (single loop for other sections)
- Channels are directly machined into the blocks surrounded by welded Copper ring. Water leak limited, No contact resistance.



Beam-dump : SAFARI, few results

<u>Calculations done using :</u>

- Beam with P=200kW,
- Particles distribution : σ =16mm and σ =6.6mm (over-focused), with or without divergence
- CW or pulsed beam (2ms)
- Misaligned beam up to 3mm

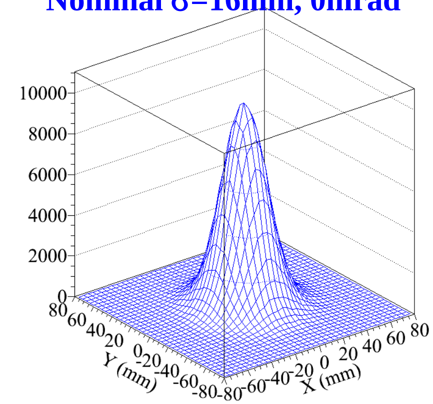


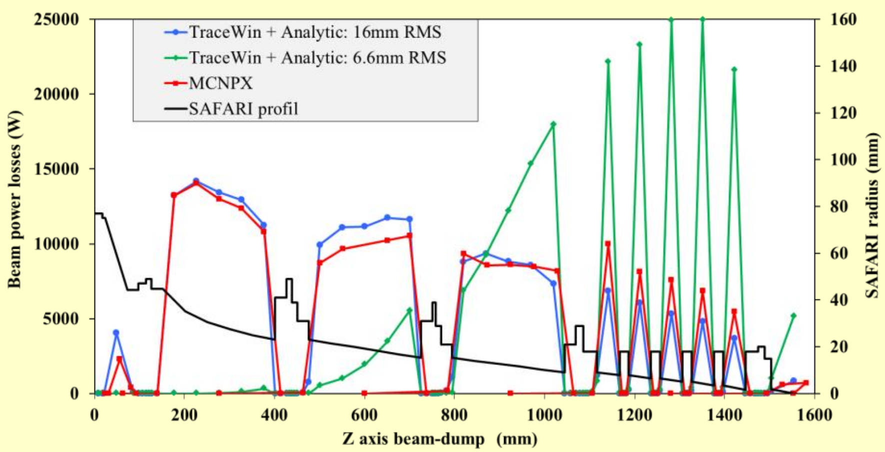
Bragg peak 1.6 mm

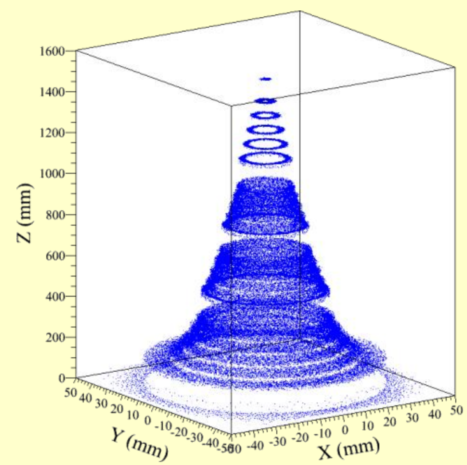
Deuterons range in Copper is equivalent to beam power deposition at the material surface

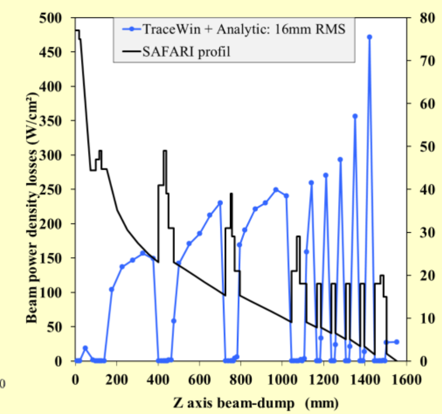
Studies done in various modes :
$\Delta \sim 0.3\%$

Nominal σ=16mm, 0mrad







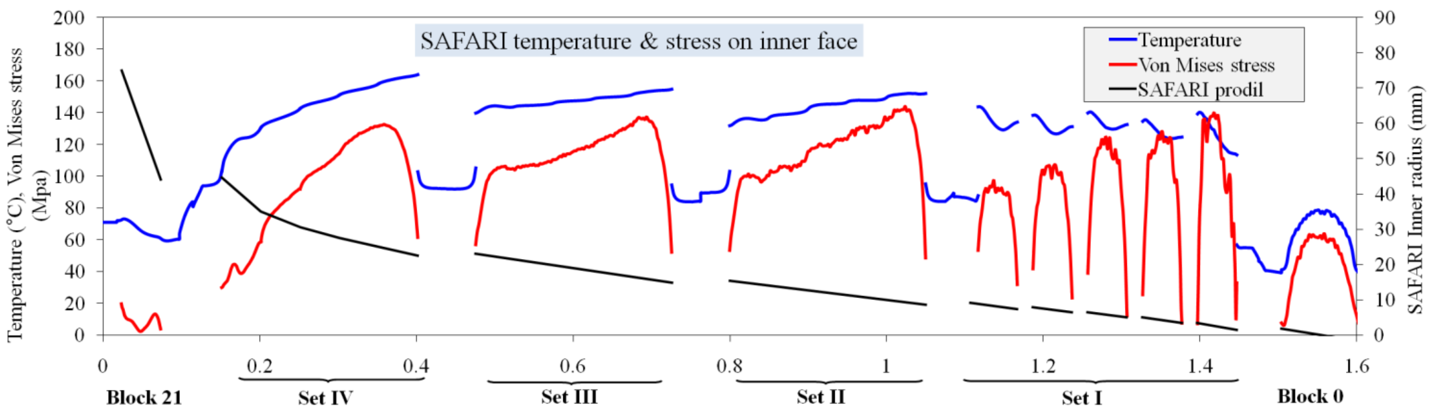


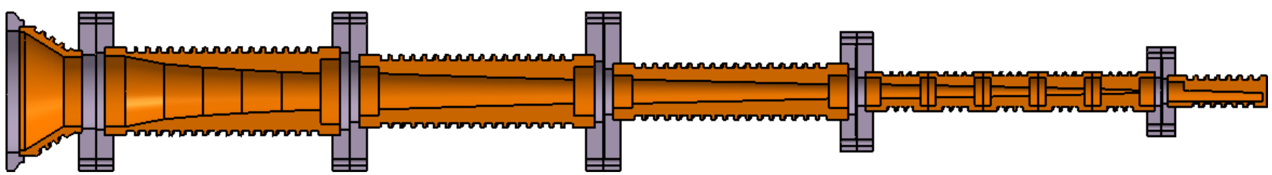
Good agreement between TraceWin+analytic calculation and MCNPX beam power losses

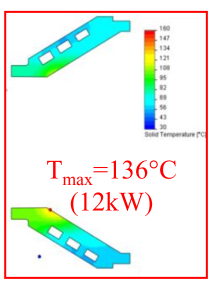
Beam-dump : SAFARI, few results

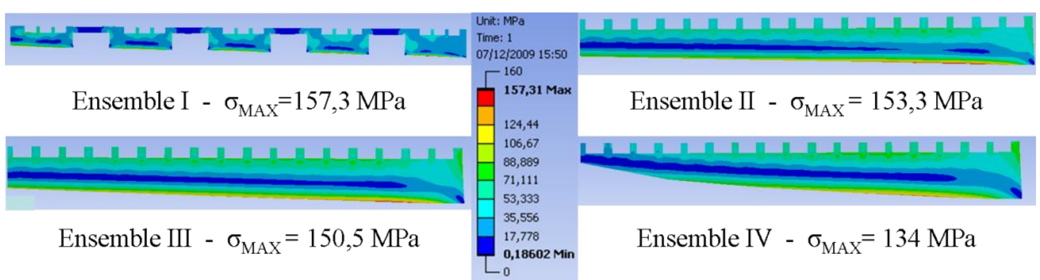
Temperature and stress on the SAFARI inner face

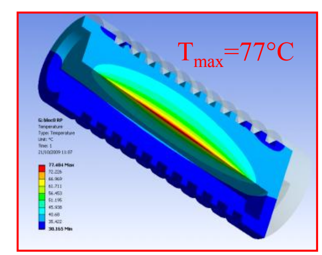
Results for nominal beam (200kW, σ =16mm, 0 mrad)









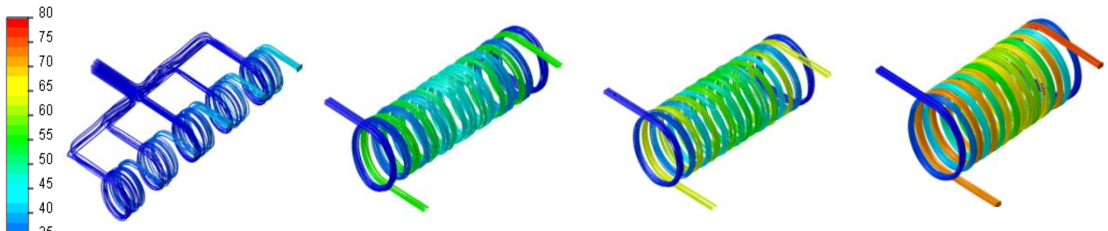


- Maximum Copper temperature ~ 160°C
- Maximum Von Mises stress ~157MPa, maximum shift = 2mm along the beam axis

=> Fulfill all thermal and mechanical requirements

Beam-dump : SAFARI, few results

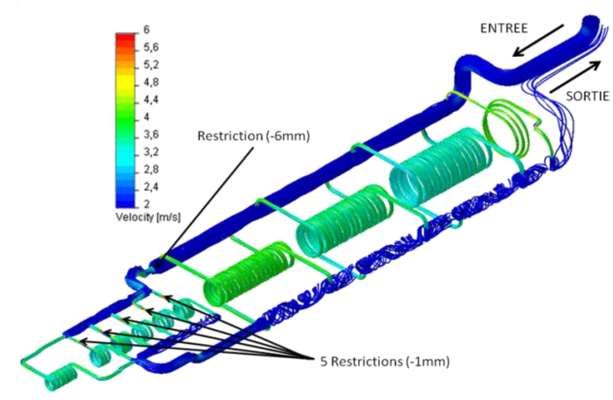
Detailed fluid studies of the cooling in the blocs using EFD V5 code



Set I : T_{max}=42°C   Set II : T_{max}=57°C   Set III : T_{max}=64°C   Set IV : T_{max}=72°C

Maximum water temperature lower than the requirement (100°)

Water pressure studies



Optimized restriction in the water distribution taken in Set I & Block 0 (last parts of SAFARI)

Impact of the over-focused beam (σ =6.6mm)

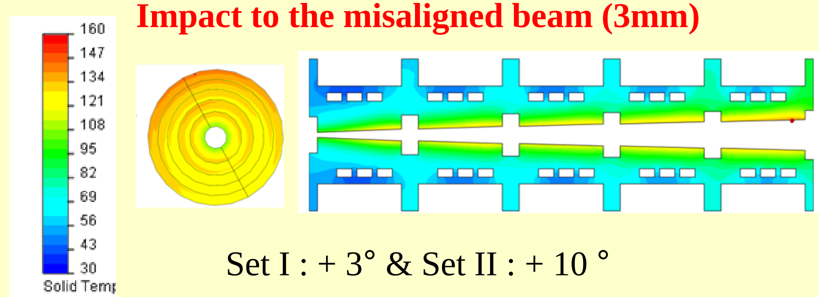
Over focalized transient study			
	transient	Tmax	σeq VM
Block 0	t = 30 ms	140 °C	207 Mpa
	t = 150 ms	195 °C	306 Mpa
	t = 1 s	260°C	> σmax
Set I	t = 10 ms	88 °C	210 MPa
	t = 20 ms	107 °C	278 Mpa
	t = 50 ms	172 °C	> σmax

Need to switch off the beam in less than 20ms

If not :

- Possibility : BS segmentation
- Material : use to Glidcop

Impact to the misaligned beam (3mm)



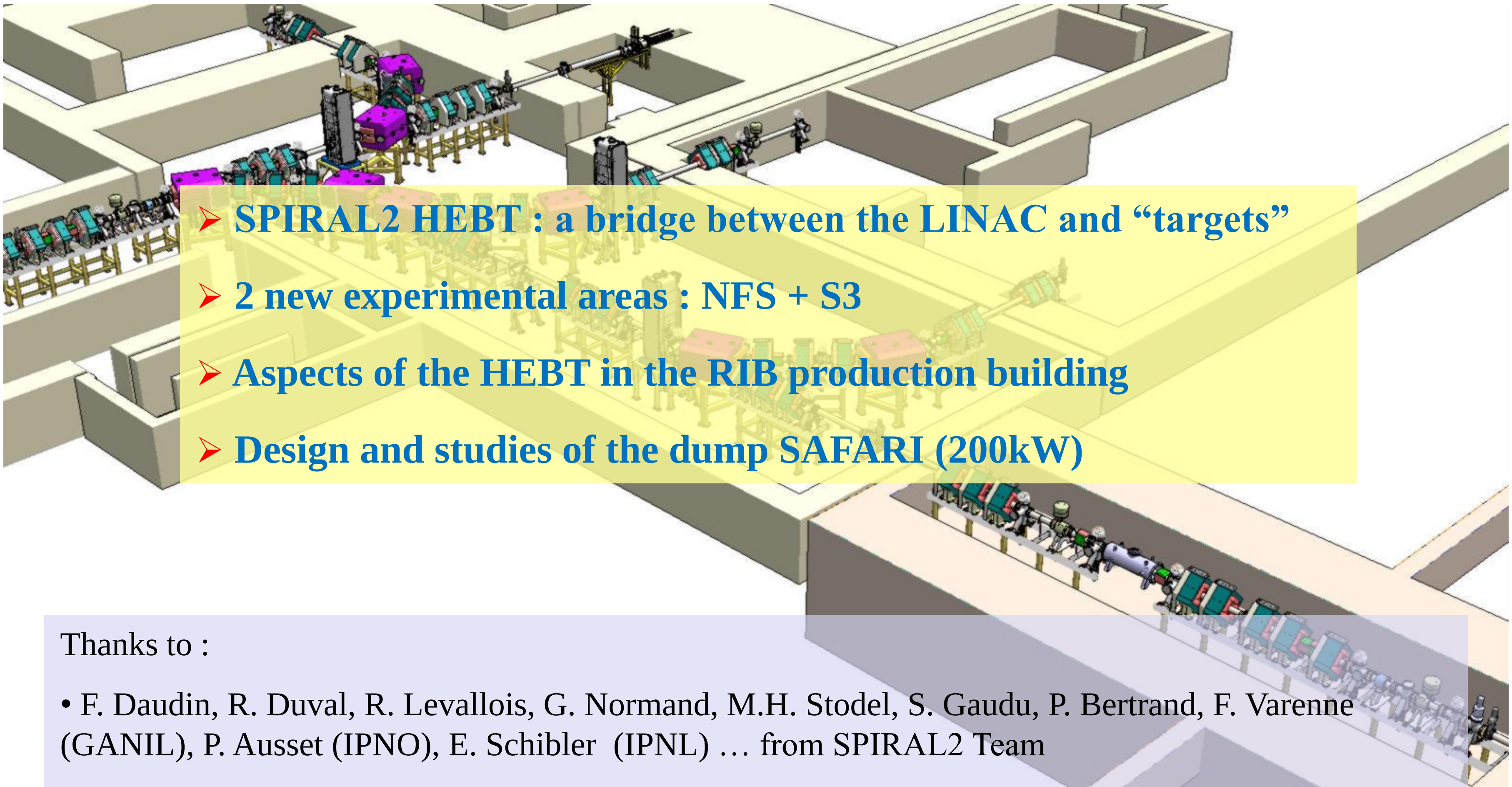
Set I : + 3° & Set II : + 10 °

Larger effect on T° & stress of over-focused beam compare to misalignment

SPIRAL2PP, WP6 task 3 (SOREQ, CIEMAT, GANIL & CNRS).
Task leader : Emilie Schibler from IPNLyon

TDR (Oct. 2010); See. Proc. : LINAC10, HB2010, PAC11, EPAC11

Summary



- ➢ **SPIRAL2 HEBT : a bridge between the LINAC and "targets"**
- ➢ **2 new experimental areas : NFS + S3**
- ➢ **Aspects of the HEBT in the RIB production building**
- ➢ **Design and studies of the dump SAFARI (200kW)**

Thanks to :

• F. Daudin, R. Duval, R. Levallois, G. Normand, M.H. Stodel, S. Gaudu, P. Bertrand, F. Varenne (GANIL), P. Ausset (IPNO), E. Schibler (IPNL) … from SPIRAL2 Team

• A. Mayoral, J. Sanz (UNED Madrid), A. Ibarra, B. Branas (CIEMAT Madrid) for the SPIRAL2PP WP6.3 collaboration