Beam Dynamics Challenges in IFMIF

HB2016, Malmö, Sweden

N. Chauvin[1], P.A.P. Nghiem[1], M. Comunian[2], C. Oliver Amoros[3], D. Uriot[1]

Nicolas.Chauvin@cea.fr

[1] Commissariat à l'Énergie Atomique et aux Énergies Alternatives, DRF/Irfu; F-91191 Gif-sur-Yvette, France

[2] INFN/LNL, Legnaro, Padova, Italy

[3] CIEMAT, Madrid, Spain

July 5, 2016

Overview

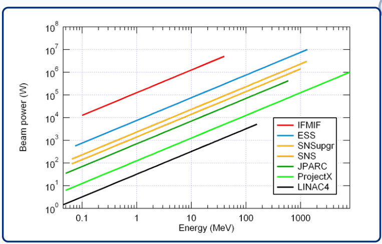
1. **IFMIF Issues & Challenges**
2. **Accelerator Matching and Tuning**
3. **Beam Loss Predictions**
4. **Massive Computing for IFMIF Beam Dynamics Simulations**

Overview

High Intensity and High Power

High Power Beam

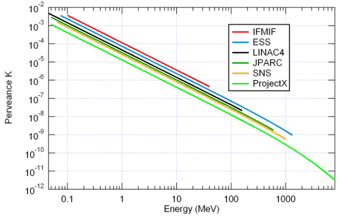
- $P = I_B \times E_B$
- Even very small losses can be harmful
- Losses can cause:
  - Activation
  - Quench of SRF cavities
  - Machine damages due to power deposition
- If 1 MW beam, losses should be kept under $\approx 10^{-6}$ of the beam
- At "low" current ($\approx$mA) or low duty cycle, *high power only at high energy*



High Intensity and High Power

High Intensity Beam

- Generalized perveance
  $$K = \frac{I_B}{I_0} \frac{2}{\beta^3 \gamma^3}$$
- High intensity means *strong space charge*, especially at low energy
- Non-liner SC forces may cause:
  - Emittance Growth
  - Beam Halo
  - ... and eventually beam losses
- Beam dynamics can be challenging *especially at low energy*



High Intensity and High Power

High intensity: accelerator matching and tuning is delicate

High power: keep the beam losses have to be kept as low as possible

The combination of high beam intensity and high beam power leads to a very challenging situation

For a detailed view on the subject:

P.A.P Nghiem *et al*, Laser and Particle Beams (2014), 32, 639–649.

High Intensity and High Power

High intensity: accelerator matching and tuning is delicate

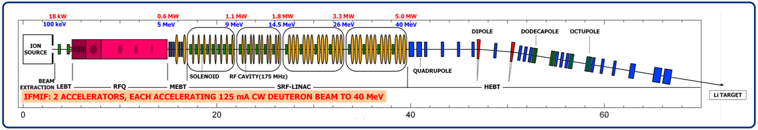
High power: keep the beam losses have to be kept as low as possible

The combination of high beam intensity and high beam power leads to a very challenging situation

For a detailed view on the subject:

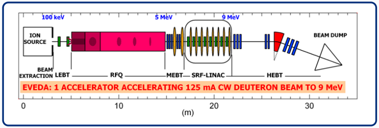
P.A.P Nghiem ***et al*****, Laser and Particle Beams (2014), 32, 639–649.**

IFMIF & LIPAc



IFMIF Accelerator: 125 mA/40 MeV D^+ beam – 5 MW

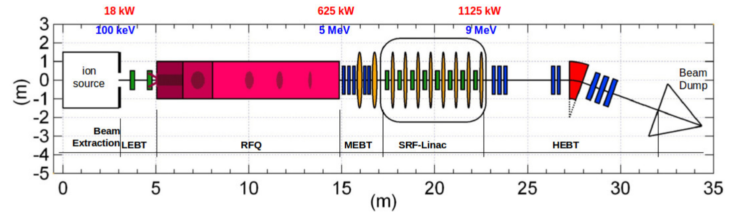
Goal of IFMIF: Produce a flux of 10^{18} $n.m^{-2}s^{-1}$ with a broad peak at 14 MeV.



Linear IFMIF Prototype Accelerator (LIPAc): 1.125 MW

Goals of LIPAc: demonstrate feasibility and validate design & technology

LIPAc Layout and Main parameters

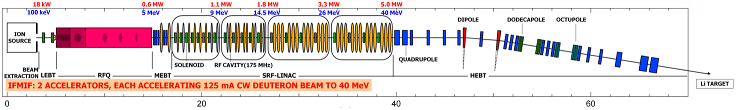


LIPAc Main Parameters

- Continuous D^+ beam
- Intensity: 125 mA
- LIPAc final energy: 9 MeV
- Hands-on maintenance

- ECR source & 2 solenoids LEBT
- 9.78 m 4-vanes RFQ @ 175 MHz
- MEBT and SFR linac (low β HWR).
- HEBT, Diagnostics Plate and Beam Dump

IFMIF Accelerator Layout and Main Parameters



IFMIF Main Parameters

- Continuous D^+ beam
- Intensity: 125 mA
- IFMIF final energy: 40 MeV
- Rectangular beam footprint on target
- SFR linac: 4 crymodules
- 3 cryomodule types
- 2 cavity types (low $\beta = 0.094$ and 0.166).
- HEBT ~40 m long with high-order multipoles

Overview

Accelerator Matching and Tuning

Considerations on Matching High Intensity Linacs

- If the beam is sent to a target, the emittance growth **in not** the primary figure of merit
- To keep a hands-on maintenance, minimizing the machine activation **is mandatory**
- Accelerator matching method achieved by beam dynamics simulations should be **transposed directly** to the real machine tuning phase.

Linac Matching

- Minimization of beam extent
- Directly minimization of the halo

⟹ **Halo Matching**

Real Machine tuning

- Minimization of beam losses
- Loss detection at 10^{-6} of the beam: micro losses

⟹ **μloss Monitors**

Accelerator Matching and Tuning

Considerations on Matching High Intensity Linacs

- If the beam is sent to a target, the emittance growth **in not** the primary figure of merit
- To keep a hands-on maintenance, minimizing the machine activation **is mandatory**
- Accelerator matching method achieved by beam dynamics simulations should be **transposed directly** to the real machine tuning phase.

Linac Matching

- Minimization of beam extent
- Directly minimization of the halo

$\Longrightarrow$ **Halo Matching**

Real Machine tuning

- Minimization of beam losses
- Loss detection at 10^{-6} of the beam: micro losses

$\Longrightarrow$ **μloss Monitors**

IFMIF Halo Matching

Halo Matching

- Multi-particle optimisation
- Numerous parameters (solenoids, quads,...)
- Non-linear problem
- Possible local minima

Particle Swarm Optimization for Halo Matching

- Explore a wide range in the space of solutions
- These kind of algorithms becomes more efficient with a high number of parameters.
- Efficient to avoid local minima
- Algorithm can be easily run in parallel on a cluster

Kennedy, J. & Eberhart, R. *Particle swarm optimization.*
Proc. of IEEE Int. Conf. on Neural Networks (1985).

IFMIF Halo Matching

Halo Matching

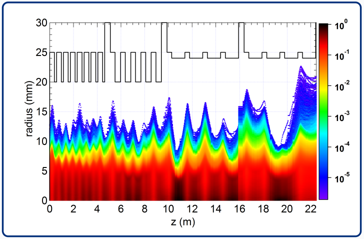
- Multi-particle optimisation
- Numerous parameters (solenoids, quads,...)
- Non-linear problem
- Possible local minima

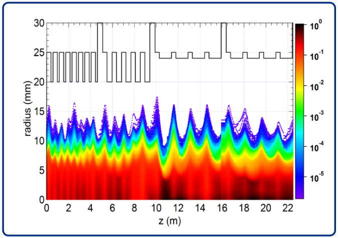
Particle Swarm Optimization for Halo Matching

- Explore a wide range in the space of solutions
- These kind of algorithms becomes more efficient with a high number of parameters.
- Efficient to avoid local minima
- Algorithm can be easily run in parallel on a cluster

Kennedy, J. & Eberhart, R. *Particle swarm optimization.*
Proc. of IEEE Int. Conf. on Neural Networks (1985).

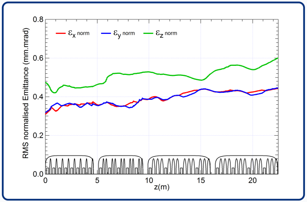
Emittance Matching vs Halo Matching

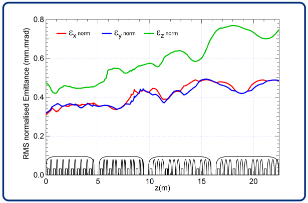




Emittance/RMS matching

Halo matching



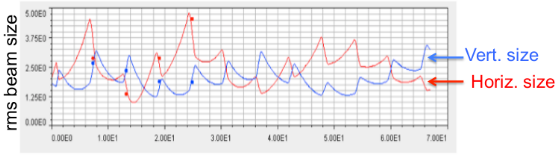


P.A.P Nghiem *et al*, Laser and Particle Beams (2014), 32, 10–118.

The SNS Experience

> *"We don't match the beam, anywhere, anytime, ever !"*
>
> Sarah M. Cousineau, HB2016, MOAM4P40.

Low-loss tune is mis-matched at beginning of SNS SCL



This is a doublet lattice

The low-loss tune is mis-matched

M.A. Plum *Challenges Facing High Power Proton Accelerators* **IPAC2013, MOXBB101**

Beam Dynamics and Beam Diagnostics for IFMIF

Diagnostics for Beam Characterization

- Beam commissioning or beam physics
- Measurements during beam commissioning only (lack of space)
- Interceptive devices for low duty cycle

→profile, emittance, halo, energy spread, bunch length

Diagnostics for Beam Tuning

- Commissioning, tuning & operating the accelerator
- To meet required specifications of current and losses
- Available for everyday beam tuning at full power: non interceptive

→beam position, beam energy, current, losses, micro-losses

J. Marroncle et al. *R&D on micro-Loss Monitors for High Intensity Linacs like LIPAc*
THAM3Y01

Overview

IFMIF Beam Losses Issues

High Beam Power

- The *whole* accelerator is concerned by **high power beam**: from 15 kW in the LEBT to 5 MW in the HEBT.
- Even a *tiny part* of the beam, when lost, represents a **significant power deposition**.

Beam Losses

- *Permanent loss* can **activate** material: hands-on? Also cooling cryogenic systems potential problems.
- *Accidental loss* leads to sudden **heat deposition** and can damage equipment.

High beam power almost all along the accelerator: meticulous and exhaustive prediction of losses is needed

IFMIF Beam Losses Issues

High Beam Power

- The *whole* accelerator is concerned by **high power beam**: from 15 kW in the LEBT to 5 MW in the HEBT.
- Even a *tiny part* of the beam, when lost, represents a **significant power deposition**.

Beam Losses

- *Permanent loss* can **activate** material: hands-on? Also cooling cryogenic systems potential problems.
- *Accidental loss* leads to sudden **heat deposition** and can damage equipment.

High beam power almost all along the accelerator: meticulous and exhaustive prediction of losses is needed

IFMIF Beam Losses Issues

High Beam Power

- The *whole* accelerator is concerned by **high power beam**: from 15 kW in the LEBT to 5 MW in the HEBT.
- Even a *tiny part* of the beam, when lost, represents a **significant power deposition**.

Beam Losses

- *Permanent loss* can **activate** material: hands-on? Also cooling cryogenic systems potential problems.
- *Accidental loss* leads to sudden **heat deposition** and can damage equipment.

High beam power almost all along the accelerator: meticulous and exhaustive prediction of losses is needed

Beam Loss Predictions

Catalogue of Losses

Double Issue

1. **Define thoroughly the loss situations in the accelerator lifetime**
2. **Define the protocols to simulate and estimate them**

Five loss situations can be determined

A. Ideal machine
B. Machine "day one"
C. Beam commissioning, tuning, exploration
D. Routine operation
E. Sudden failure

Catalogue of Losses

Affects all the subsystems: hot points, beam stop system velocity, limitations for control system, maximum beam power for operation, dynamic range of diagnostics, etc.

Double Issue

1. **Define thoroughly the loss situations in the accelerator lifetime**
2. **Define the protocols to simulate and estimate them**

Five loss situations can be determined

A. Ideal machine
B. Machine "day one"
C. Beam commissioning, tuning, exploration
D. Routine operation
E. Sudden failure

Catalogue of Losses

Affects all the subsystems: hot points, beam stop system velocity, limitations for control system, maximum beam power for operation, dynamic range of diagnostics, etc.

Beam Loss Predictions

Catalogue of Losses

Double Issue

1. **Define thoroughly the loss situations in the accelerator lifetime**
2. **Define the protocols to simulate and estimate them**

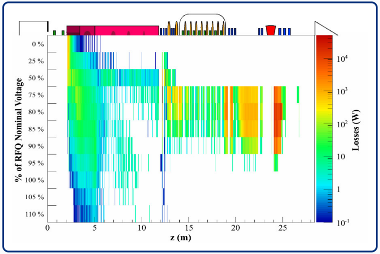
Five loss situations can be determined

A. Ideal machine
B. Machine "day one"
C. Beam commissioning, tuning, exploration
D. Routine operation
E. Sudden failure

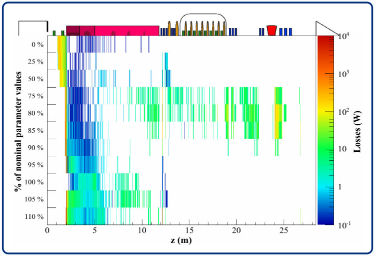
Catalogue of Losses

Affects all the subsystems: hot points, beam stop system velocity, limitations for control system, maximum beam power for operation, dynamic range of diagnostics, etc.

Example for LIPAc: Sudden Failure



Beam power lost in case of RFQ failure



Power lost in case of LEBT and RFQ failure

- 10 W losses in the SRF linac for 90% of the RFQ voltage
- Less losses in SRF linac and HEBT in case of failure of the three elements

P.A.P. Nghiem, N. Chauvin, M. Comunian, C. Oliver AND D. Uriot
A catalogue of losses for a high power, high intensity accelerator
Laser and Particle Beams (2014), 32, 461–469.

BD Challenges IFMIF
Issues & Challenges
HE/HP Issues
IFMIF & LIPAc Layout
Matching & Tuning
IFMIF Halo Matching
Emittance vs Halo
BD & Diagnostics
18 Beam Losses
Massive Computing
Goals and Method
Results: Densities
Results: Phase Space
Results: Beam Losses

Overview

Massive Computing for Beam Dynamics Simulations

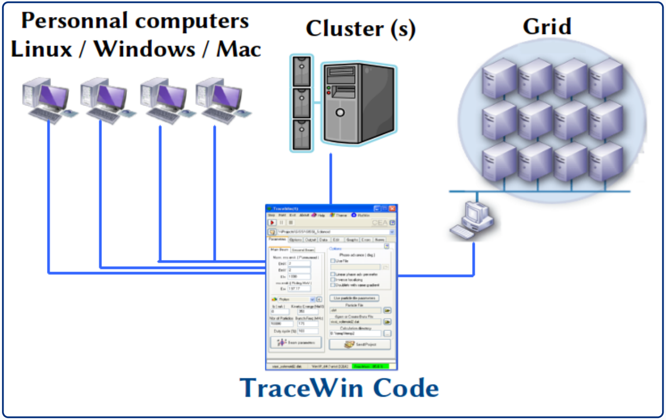
Goals

- Simulations with 10^9 macro-particles
- Halo formation and longitudinal dynamics
- Statistical error studies
- Improvement of simulation tools

Method

- TraceWin code is used
- Distributed calculations on several machine types
- Massive hard drive storage (70 To HDD)
- Dedicated data analysis software has been written (using ROOT Data Analysis Framework)

Massive Computing for Beam Dynamics Simulations



Distributed calculations using the TraceWin code

Simulation of IFMIF–LIPAc
Simulation Conditions

Some numbers...

- Simulation with the **actual** number of particles in a bunch: $\mathbf{4.7\times10^9}$
- Storage of 6D beam distributions at 2000 positions along the accelerator (every 2cm): **38 To**
- Computing: **25 days** running on **170 CPUs**
- Post processing: ~12 hours running on 30 CPUs

Used Accelerator Models

- Initial conditions: particles are randomly generated from a simulation of the ion source extraction system (Axcel-INP)
- LEBT: space charge compensation profile determined with a PIC self-consistent code
- RFQ, SRF Linac and HEBT are modeled by field maps (1D or 3D)

Some numbers...

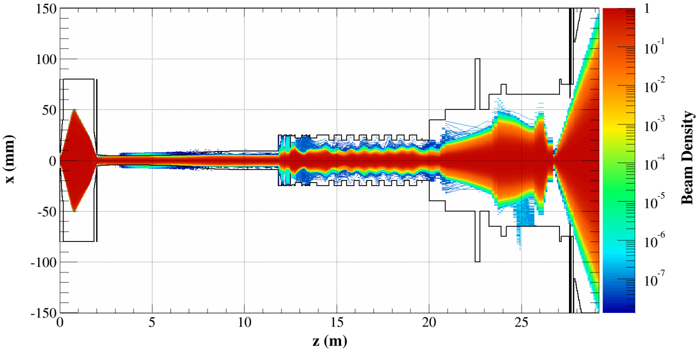
- Simulation with the **actual** number of particles in a bunch: **4.7×10^9**
- Storage of 6D beam distributions at 2000 positions along the accelerator (every 2cm): **38 To**
- Computing: **25 days** running on **170 CPUs**
- Post processing: ~12 hours running on 30 CPUs

Used Accelerator Models

- Initial conditions: particles are randomly generated from a simulation of the ion source extraction system (Axcel-INP)
- LEBT: space charge compensation profile determined with a PIC self-consistent code
- RFQ, SRF Linac and HEBT are modeled by field maps (1D or 3D)

Simulation Results

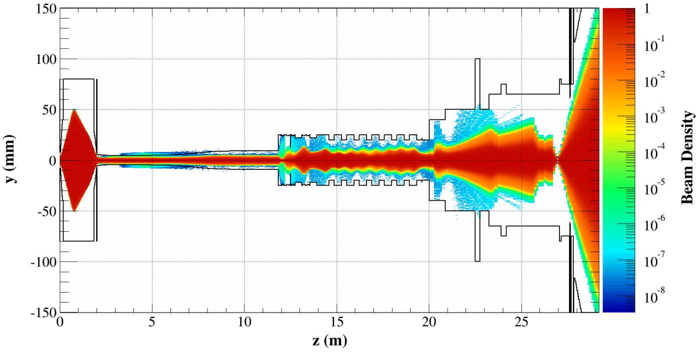
Beam Density along the LIPAc



Beam Density: X plane

Simulation Results

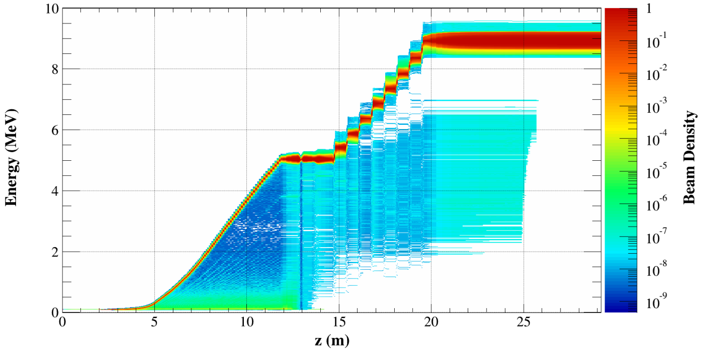
Beam Density along the LIPAc



Beam Density: Y plane

Simulation Results

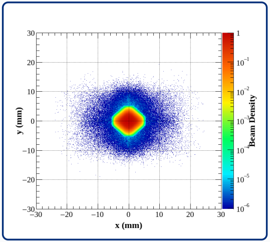
Beam Density along the LIPAc



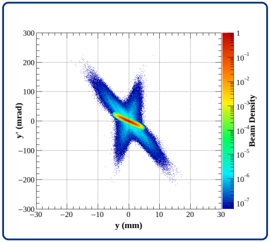
Beam Density: energy

Simulation Results

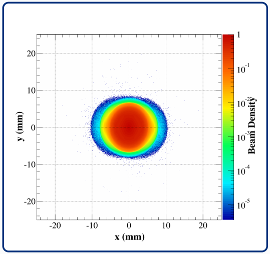
Beam Distributions in Phase Spaces – Transverse Plane



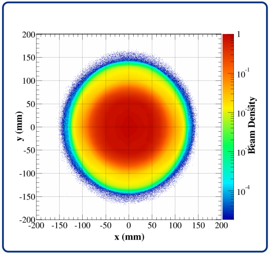
xy distribution after RFQ



yy' distribution after RFQ



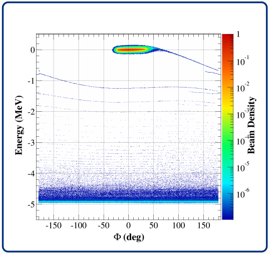
xy distribution after SRF-Linac



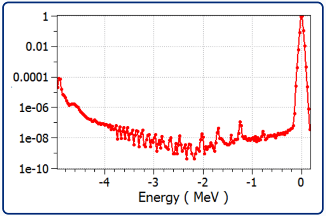
xy distribution on beam dump

Simulation Results

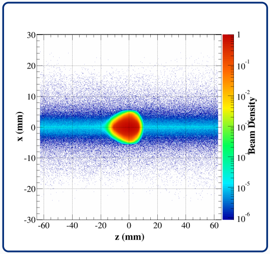
Beam Distributions in Phase Spaces – Longitudinal Plane



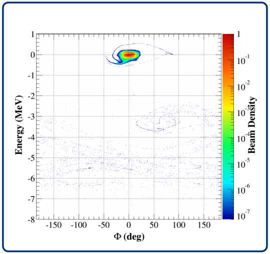
ΦΔE distribution after RFQ



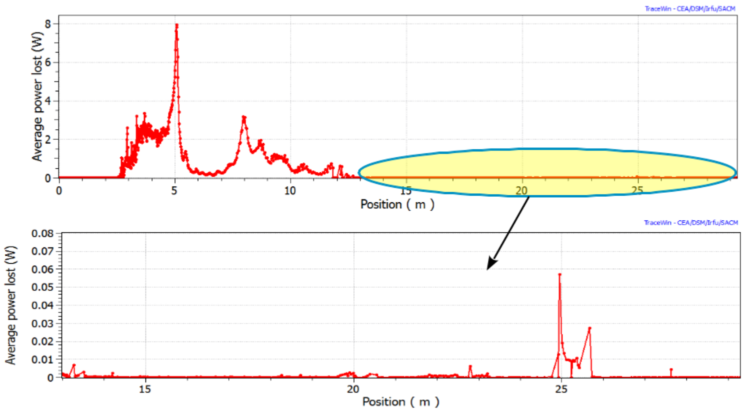
ΔE distribution after RFQ



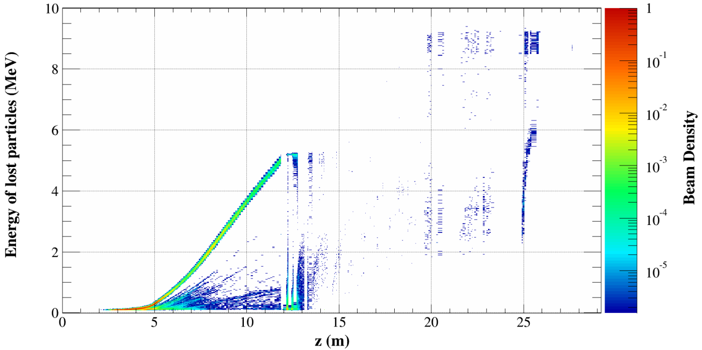
zx distribution after RFQ



ΦΔE distribution after SRF-linac

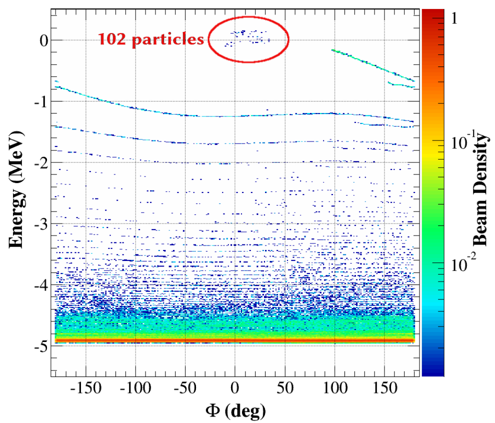


Beam losses in Watt through the accelerator



Energy of the lost particles

Simulation Results
Beam Losses in LIPAc



Distribution, after the RFQ, of the particles that will be lost downstream.

Conclusions

Conclusion

- ”Halo matching” of the IFMIF linac has been simulated
- µloss monitors feasibility has been demonstrated
- Cautious prediction of losses
- High statistics multi-particle simulations
- Beam commissionong of LIPAc has started in Japan

M. Comunian et al. *IFMIF-EVEDA RFQ, Measurement of Beam Input Conditions and Preparation to Beam Commissioning* **TUPM4Y01**

Perspectives

- New studies in the framework of IFMIF/DONES
- Beam dynamics activities for SRF-linac and HEBT
- Goal: to be ready for IFMIF/DONES construction in 2020

Conclusions

Conclusion

- ”Halo matching” of the IFMIF linac has been simulated
- μloss monitors feasibility has been demonstrated
- Cautious prediction of losses
- High statistics multi-particle simulations
- Beam commissionong of LIPAc has started in Japan

M. Comunian et al. *IFMIF-EVEDA RFQ, Measurement of Beam Input Conditions and Preparation to Beam Commissioning* **TUPM4Y01**

Perspectives

- New studies in the framework of IFMIF/DONES
- Beam dynamics activities for SRF-linac and HEBT
- Goal: to be ready for IFMIF/DONES construction in 2020

Thank you for your attention !