High Intensity Beams Activities at CEA/Saclay

UCANS V, INFN Legnaro, Italia.

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Overview

1. **Issues & Challenges for High Power Accelerators**
   - High Intensity and High Power Issues
   - Beam Losses Predictions
   - Accelerator Matching and Tuning
2. **Developments Dedicated to High Intensity Beams**
   - Beam Creation
   - Beam Acceleration
   - Beam Diagnostics
3. **The IPHI Project, a High Intensity Proton Injector**
   - Presentation
   - IPHI Goals
   - IPHI Status

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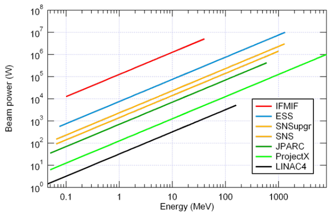
High Intensity and High Power

High Power Beam

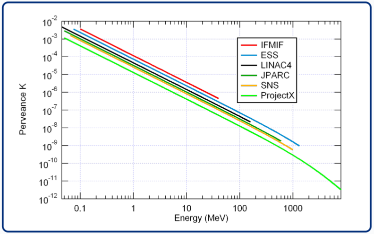
- $P = I_B \times E_B \times d.c.$
- Even very small losses can be harmful
- Losses can cause:
    - Activation
    - Quench of SRF cavities
    - Machine damages due to power deposition
- If 1 MW beam, losses should be kept under $\approx 10^{-6}$ of the beam
- At "low" current (≈mA) or low duty cycle,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



High Intensity and High Power

High Intensity Beam

- Generalized perveance
  $$K = \frac{1}{2\pi\varepsilon_0} \frac{qI_B}{mc^3\beta^3\gamma^3}$$
- 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



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

Dedicated Methods for High Intensity/High Power Beams

1. Protocol for **beam losses prediction**
2. Method for **beam optimization**
3. Strategy for **beam losses measurement**

P.A.P. Nghiem, N. Chauvin *et al.*
Advanced Concepts and Methods for Very High Intensity Accelerators.
Laser and Particle Beams, vol. 32, p. 639–649, 2014.

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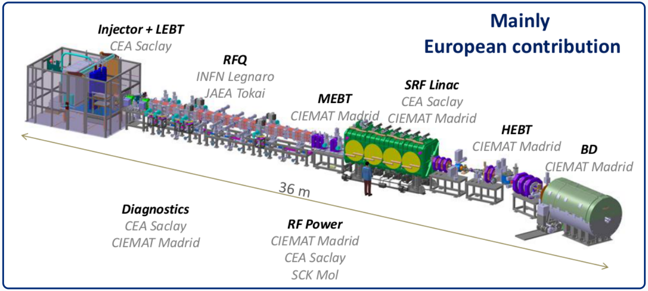
High Intensity and High Power
Linear IFMIF Prototype Accelerator

These beam dynamics studies have been performed in the framework of the **IFMIF/EVEDA collaboration** but the **very same methods** can be applied to **any kind** of high intensity/high power accelerator



- D^+ beam
- Intensity: 125 mA
- Energy: 9 MeV
- Duty Factor: c.w.
- SC HWR linac
- Frequency: 175 MHz

Beam Losses Issues

High beam power

- The *whole* accelerator is concerned by **high power beam** (LIPAc case: from 15 kW in LEBT to 1.125 MW in HEBT).
- Even a *tiny part* of the beam, when lost, represents a **significant power deposition**.

Beam Losses

- **Permanent losses** can **activate** material: hands-on maintenance and cooling cryogenic systems potential problems. If losses < 1 W/m, for a MW beam $\Longrightarrow$ 1 particle over 10^6 (*microlosses*).
- **Accidental losses** lead to sudden **heat deposition** and can damage equipment.

Meticulous and exhaustive prediction of losses is needed

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Beam Losses Study Procedure

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

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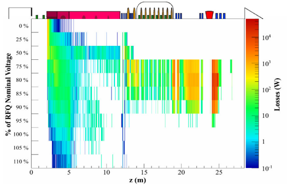
An Example, a Catalogue of Losses for LIPAc

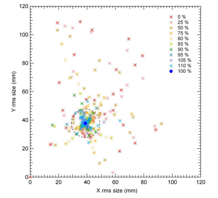
- Code used: TraceWin
- Simulations were performed with 10^6 particles
- Simulations were performed at full beam intensity
- Error studies with 500 cases
- Dedicated data analysis codes have been developed

Affect all the subsystems

Hot points, beam stop velocity, control system, max. beam power for each phase, dynamic range of diagnostics, etc.



Beam power lost in case of RFQ failure



Beam RMS size on the beam dump

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..

Considerations on Matching High Intensity Linacs

- If the beam is sent on 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 during the tuning phase.

Linac Matching

- Minimization of beam extent
- Directly minimization of the halo

$\Rightarrow$ **Halo Matching**

Real Machine tuning

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

$\Rightarrow$ **μloss Monitors**

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- Multi-particle optimisation (up to 10^6)
- Numerous parameters (solenoids, quads, cavities,...)
- Non-linear problem
- Possible local minima

Particle Swarm Optimisation algorithm has been chosen
A population based stochastic optimization technique

PSO 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.

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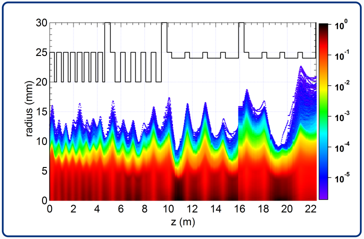
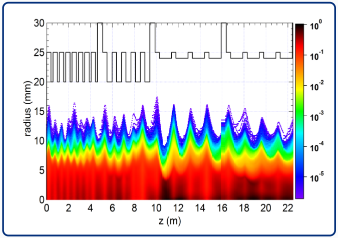
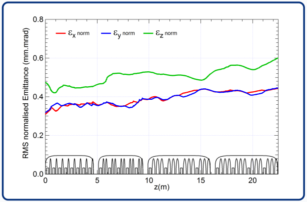
Emittance Matching vs Halo Matching

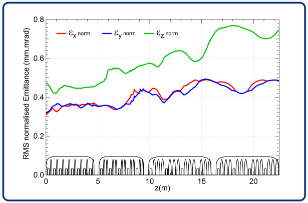




Emittance/RMS matching

Halo matching

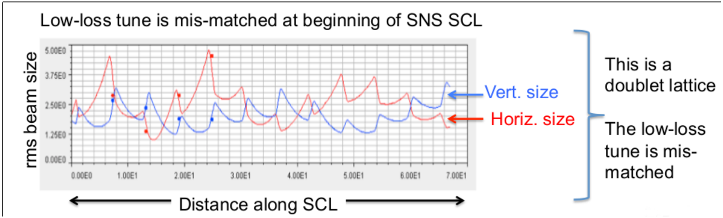




P.A.P Nghiem *et al*, Laser Part. Beams 32, 10-118 (2014).

The SNS Experience

> *"Perhaps it is better to mismatch the core of the beam to allow better transmission (lower beam loss) for the part of the distribution that causes beam loss (i.e. the tails or halo of the beam)."*
>
> M.A. Plum



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

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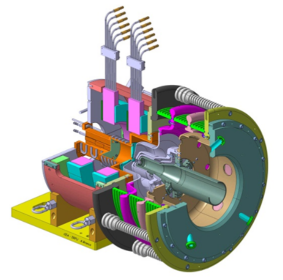
Light Ion Production
SILHI Source

High intensity ion sources

- Developed in Saclay since 1994
- Mainly ECR 2.45 GHz ion sources
- Particles: H^+, D^+, He^+.
- Pulsed to c.w. beam
- Beam intensity from 10 mA to 140 mA
- Projects like SPIRAL 2, FAIR proton linac, IFMIF.
- A ”low current” version (SILHI 2, 50 mA) is commercially available (`www.pantechnik.com`)

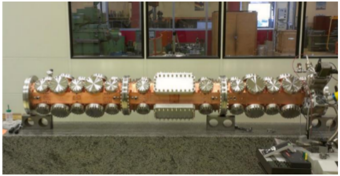


2.45 GHz SILHI ion source

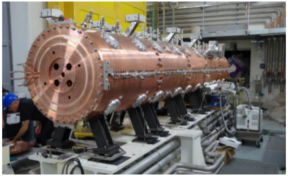
RFQ

Bunching, focusing and bunching

- Expertise in simulation, RF and mechanics design and tuning of RFQs.
- Design and/or fabrication and/or tuning of the RFQs for LINAC4 and SPIRAL2
- In the coming years, RFQ for ESS: design and realisation of the RFQ, tuning, RF conditioning, beam test with source + LEBT from Catania.
- IPHI is a local R&D project to accelerate a 100 mA cw beam to 3 MeV (see later).



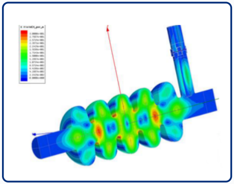
LINAC 4 RFQ, first beam tests at CERN in March 2013

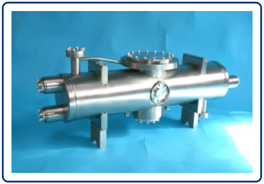


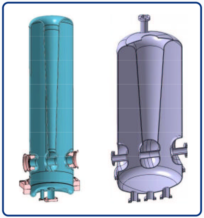
SPIRAL2 RFQ, installed at GANIL in October 2014

Superconducting RF Technology

- Based on bulk Niobium, SRF technology is used for most of the linear accelerators since 2000: EU-CARE (SRF, HIPPI), XFEL, ESS, IFMIF, SPIRAL2...
- Simulation, design & realisation of all the critical components: cavities, couplers, tuners.
- All types of cavities: multi-cells, HWR, QWR – Low β, High β.
- R&D programs for high gradient cavities: mechanical and chemical processing, multilayer...

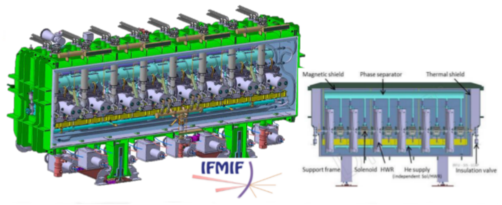






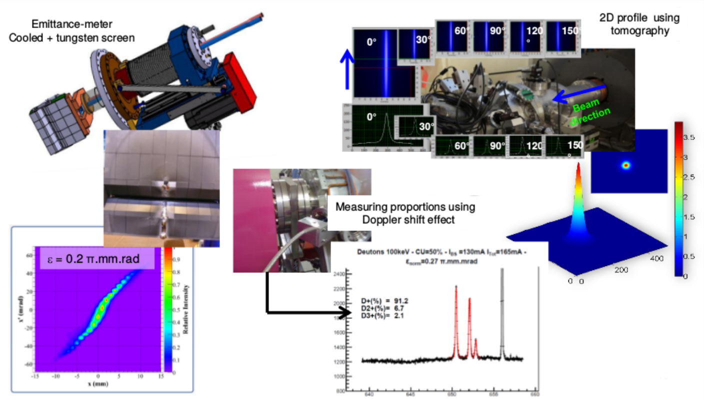
From SC Cavities to Cryomodules

- Design of cryomodules for ESS, SPIRAL2, SARAF, IFMIF…
- Coupler, cavity assembly, alignment, cavity insertion into cryostat.
- Infrastructure for cryomodules integration (clean room).
- From prototypes to large series (103 cryomodules for XFEL).



Beam Diagnostics

- Beam characterisation: intensity, position, profile, proportions, emittance, energy, beam losses.
- High beam power: ~10 kW/cm^2.
- Low and high energy.

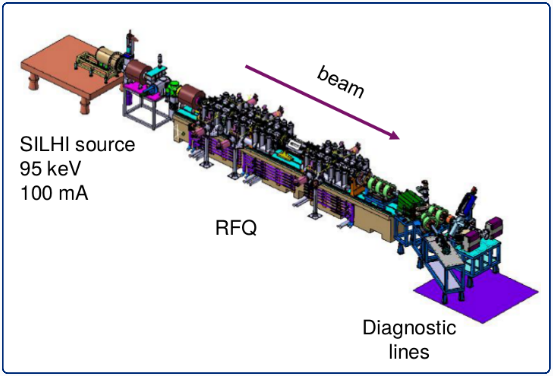


Overview

IPHI Scheme and Parameters

Main parameters

- SILHI ion source: 100 mA, 95 keV, cw
- 4-vanes RFQ: 100 mA, 3 MeV, 352 MHz
- Diagnostic line: 100 mA, 3 MeV, beam dump.



IPHI Initial Goals

1. Development and validation of beam dynamics codes
   - TraceWin
   - Space Charge compensation simulations
2. Beam characterisation
   - Beam properties for the following accelerating structures
   - ESS and future high current accelerator
3. Development and tests of beam diagnostics that can be used in the future high intensity accelerators
4. Reliability tests and fast re-starting procedures
   - Validation of technological choices
   - Application for Accelerator Driven System
5. Increase the laboratory competences in high intensity/high power accelerator commissioning and tuning
   - Measurement and RF tuning of the RFQ cavity
   - Beam commissioning and operation of high intensity accelerator

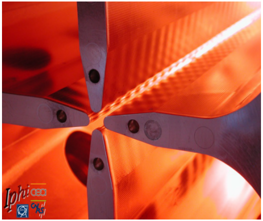
IPHI Status and Future

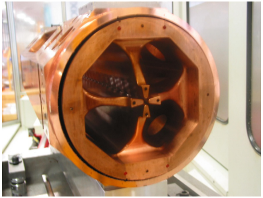
Commissioning

- RF conditioning has started:
  600 kW has been injected in the RFQ cavity at 1% duty cycle.
- Beam commissioning: end of 2015.

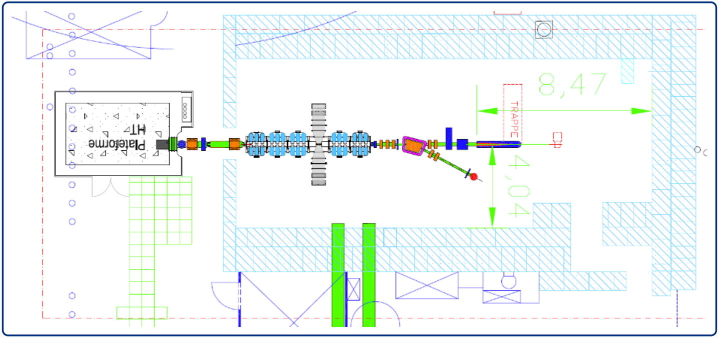
Exploitation

- Proton beam 100 mA @ 3 MeV, cw or pulsed.
- Beginning of 2016: ESS tests (pulsed mode @ 4% d.c.) and replacement of the RF sources.
- End of 2016 and 1st semester of 2017: possible beam availability for neutron production experiments.





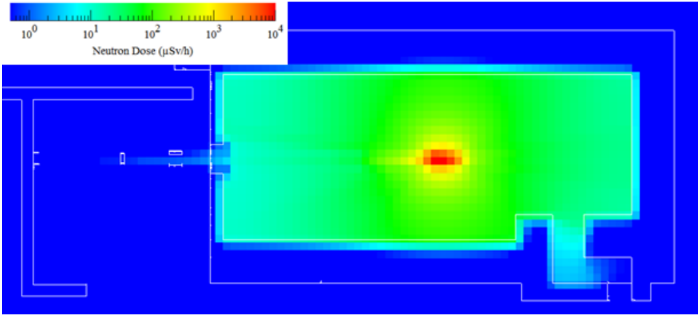
IPHI Vault



- Replace the beam dump with target + moderator + detectors
- Shielding is necessary
- Room for beam rastering on the target (beam dynamics simulations needed) ?

IPHI Vault

Radioprotection/Neutron Production



- Now: Nickel beam dump to limit neutron production
- Neutrons production: **2×10^9 n.s-^{1}** @ full beam power (shielding is needed around the beam dump)
- With Be target $\Longrightarrow$ **$\approx 2\times10^{13}$ n.s-^{1}**...

Conclusions and Perspectives

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- Advanced beam dynamics considerations for high intensity/high power beams.
- Developments and competences on high intensity accelerators in Saclay.
- IPHI beam commissioning should started by the end of 2015.
- Available beam by the end of 2016.

Perspectives

- IFMIF/LIPAc beam commissioning: a high intensity/high power accelerator laboratory.
- Experiment and tests on IPHI for neutrons production: target, moderator, **radio-protection shielding**.
- Increasing interest for compact neutron sources in Saclay (LLB, Irfu...)

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