Halo Matching for High Intensity Linacs and Dedicated Diagnostics

HB2014, East Lansing, USA.

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November 11, 2014

Overview

1. **Issues & Challenges for High Power Accelerators**
   - High Intensity and High Power Issues
   - Accelerator Matching and Tuning
2. **Linac Halo Matching**
   - PSO Algorithm
   - Linac Halo Matching Using Particle Swarm Optimisation
   - Emittance Matching vs Halo Matching
3. **Micro Loss Monitors**
   - Diamonds as Micro Loss Monitors
   - Characterization of the diamond crystals
   - Front End Electronics and Implantation

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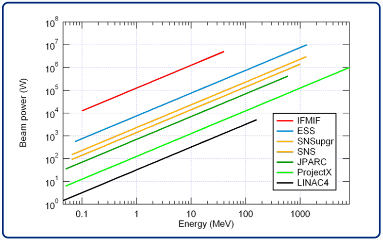
3. **Micro Loss Monitors**

High Intensity and High Power

High Power Beam

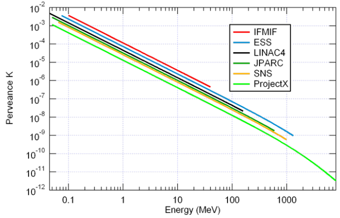
- $P = I_B \times E_B$
- Even very small losses can be harmful
- Losses can cause:
  - Activation
  - Quench of SRF cavities
  - Machine damages due to power deposition
- If 1 MW beam, losses should be kept under $\approx 10^{-6}$ of the beam
- At "low" current (≈mA) or low duty cycle, *high power only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



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 more detailed view on the subject:

P.A.P. Nghiem *New Methods and Concepts for Very High Intensity Beams* **WEO4LR01**

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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

$\Rightarrow$ **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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   - Emittance Matching vs Halo Matching

3. Micro Loss Monitors

Halo Matching

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

The Particle Swarm Optimisation algorithm has been chosen

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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The PSO basic principle

Particle Swarm Optimization
A population based stochastic optimization technique

1. **Each individual (i.e. particle) of the population is a candidate solution of the problem**
   A particle represents a set of parameters: solenoid field, quadrupoles, sextupoles, gradients ...
2. **The particles are initially randomly generated in the hyperspace of solution**
   Each parameter can vary in a given range.
3. **The particles are evaluated by the function to minimize**
   For each set of parameters, the a fitness value is calculated

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

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The PSO Basic Principle

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4. **The particles are set in motion in the space of solutions. At each time step their velocity is change toward its best location and toward the global best (best particle of the swarm). Acceleration is weighted by a random term.**

$$\mathbf{V}_i(t) = \mathbf{r}_1(\hat{\mathbf{g}} - \mathbf{x}_i(t)) + \mathbf{r}_2(\hat{\mathbf{x}}_i - \mathbf{x}_i(t))$$

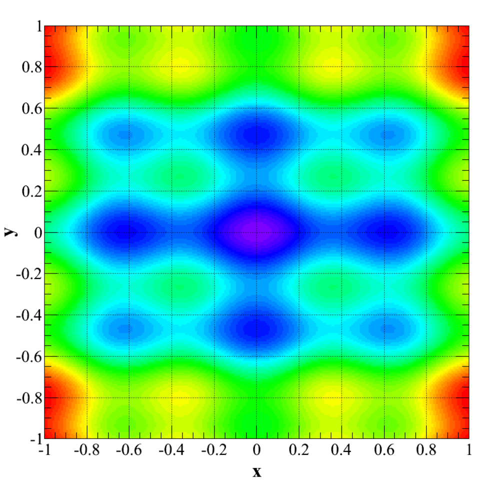
$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{V}_i(t)$$

where $\hat{\mathbf{g}}$ and $\hat{\mathbf{x}}_i$ are the global and local best and $\mathbf{r}_1$ and $\mathbf{r}_2$ are random vector $U[0,1]$.

PSO Example

Function to minimize:

$$f(x, y) = x^2 + 2y^2 - 0.3cos(3\pi x) - 0.4cos(4\pi y) + 0.7$$



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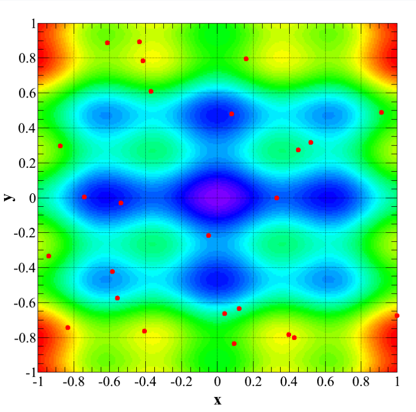

PSO conditions

- 20 particles
- $-1 \quad x_i \quad 1$

Step 0

PSO example

Function to minimize :

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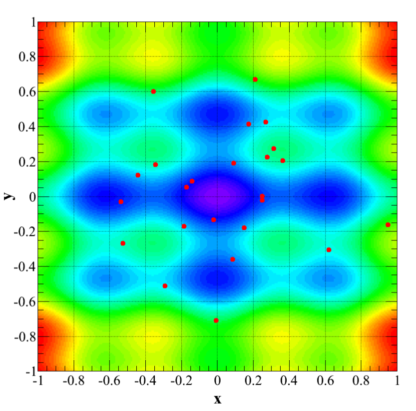

PSO conditions

- 20 particles
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Step 2

PSO example

Function to minimize :

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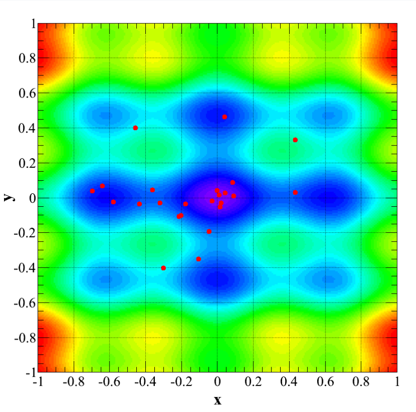


PSO conditions

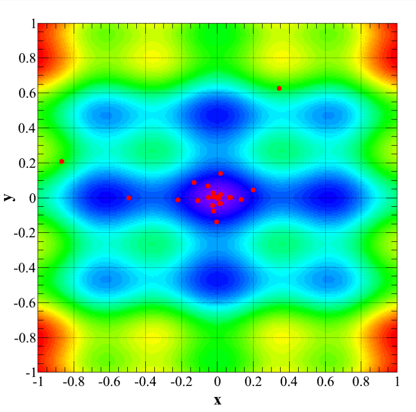
- 20 particles
- $-1 \quad x_i \quad 1$

Step 5

PSO example

Function to minimize :

$$f(x, y) = x^2 + 2y^2 - 0.3cos(3\pi x) - 0.4cos(4\pi y) + 0.7$$



PSO conditions

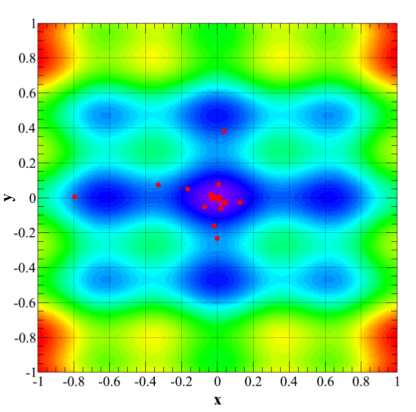
- 20 particles
- $-1 \quad x_i \quad 1$

Step 8

PSO example

Function to minimize :

$$f(x, y) = x^2 + 2y^2 - 0.3cos(3\pi x) - 0.4cos(4\pi y) + 0.7$$



PSO conditions

- 20 particles
- $-1 \quad x_i \quad 1$

Step 10

PSO example

Function to minimize :

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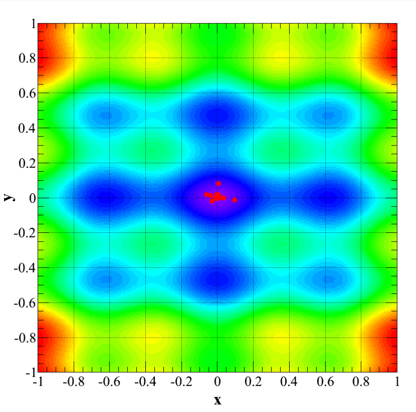

PSO conditions

- 20 particles
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Step 15

PSO example

Function to minimize :

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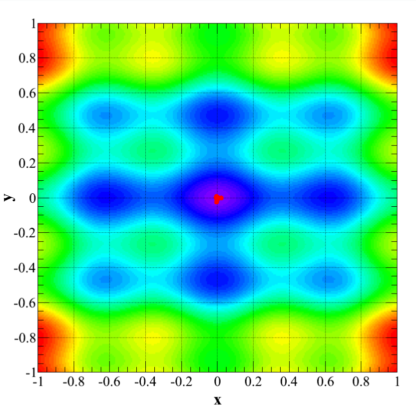


PSO conditions

- 20 particles
- $-1 \quad x_i \quad 1$

Step 20

Linac Halo Matching Using Particle Swarm Optimisation

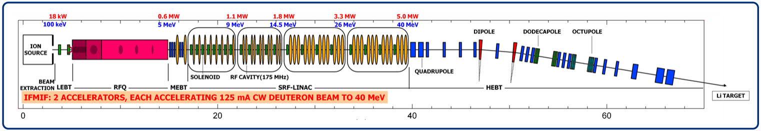
- Parameters to be optimized: solenoids fields, quadrupoles, sextupoles gradients...
- Fitness function to be minimized:

$$Fitness = \sum_{i=1}^{N_p} C_n(if(r_i > r_n))$$

where C_n are constants that can be increased as r_n increase. For example, r_15 = 15 mm, C_15=1, r_16 = 16 mm, C_16=10 ...

- Code used: TraceWin
- Number or beam particles in TraceWin: 10^5
- Number of PSO particles: ≈50

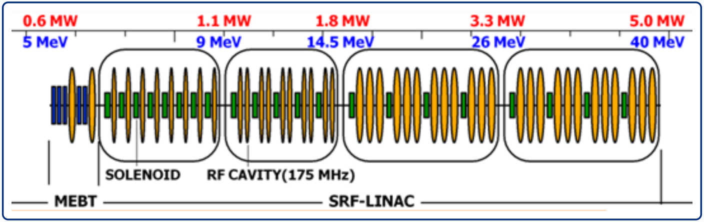
IFMIF Accelerator Layout and Main Parameters



IFMIF Main Parameters

- Deuteron beam
- Continuous beam
- Intensity: 125 mA
- Frequency: 175 MHz
- Final energy: 40 MeV
- Hands-on maintenance
- Linac: 4 crymodules
- Linac: solenoids and HWR cavities

IFMIF Linac Layout



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- Intensity: 125 mA
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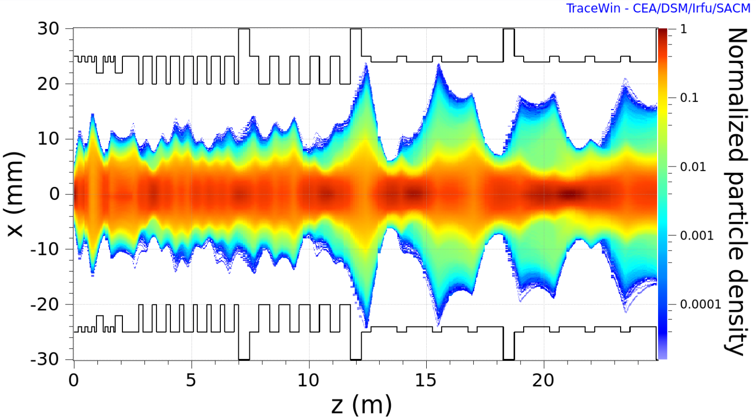
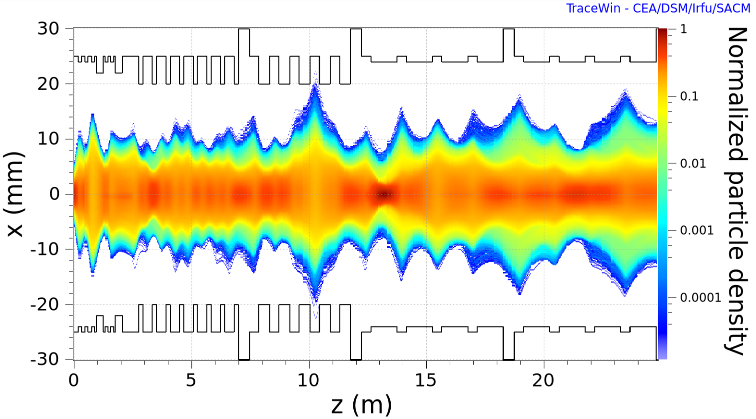
- Linac: 4 crymodules
- Linac: 21 solenoids and 42 HWR cavities

IFMIF Linac Halo Matching



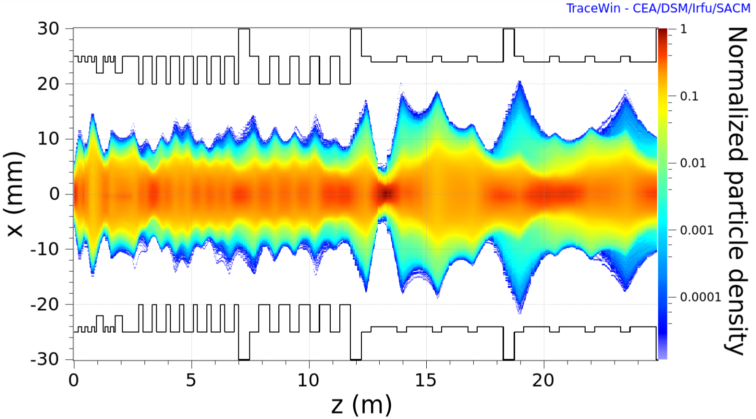
Step 0

IFMIF Linac Halo Matching



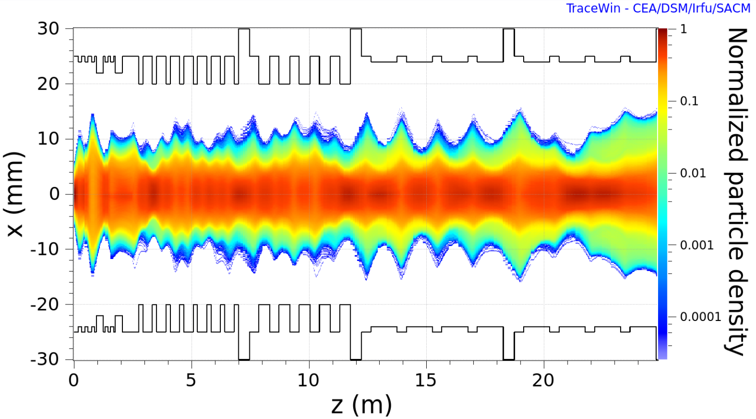
Step 1

IFMIF Linac Halo Matching



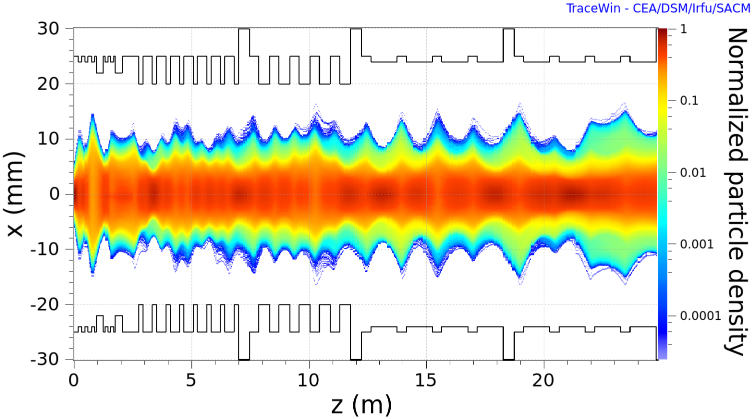
Step 4

IFMIF Linac Halo Matching



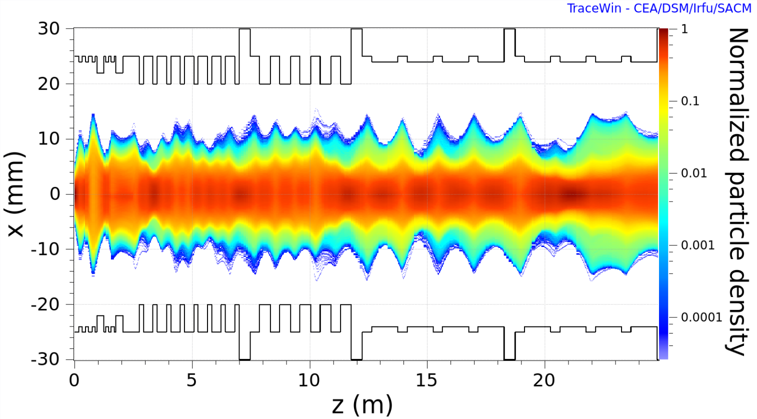
Step 8

IFMIF Linac Halo Matching



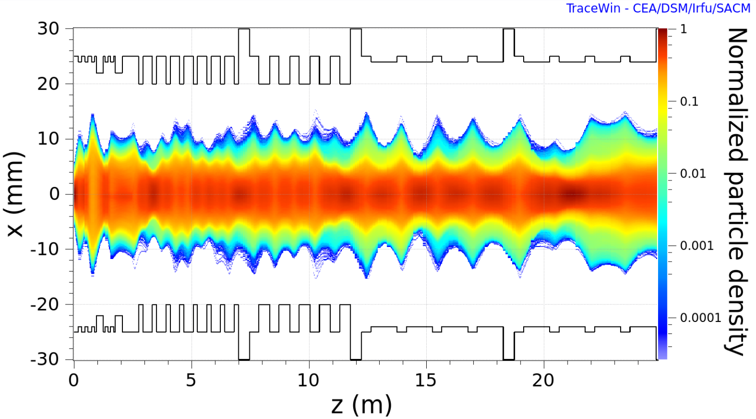
Step 10

IFMIF Linac Halo Matching



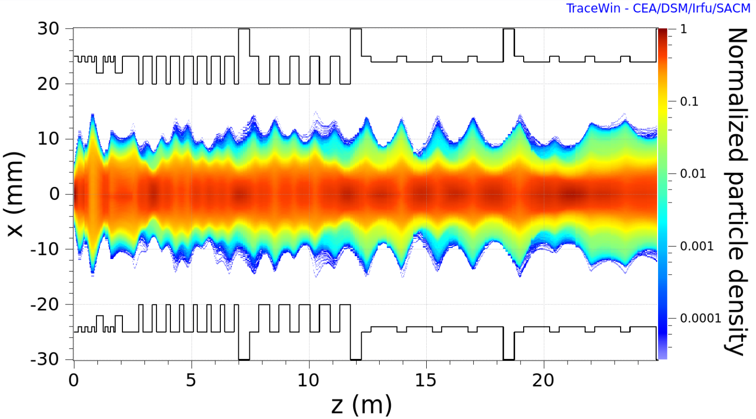
Step 15

IFMIF Linac Halo Matching



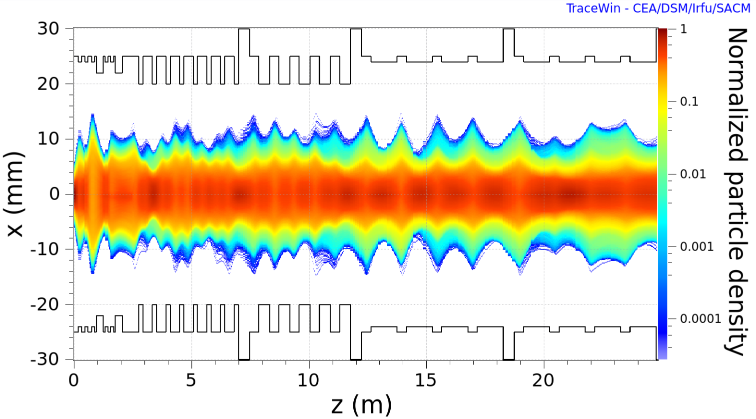
Step 25

IFMIF Linac Halo Matching



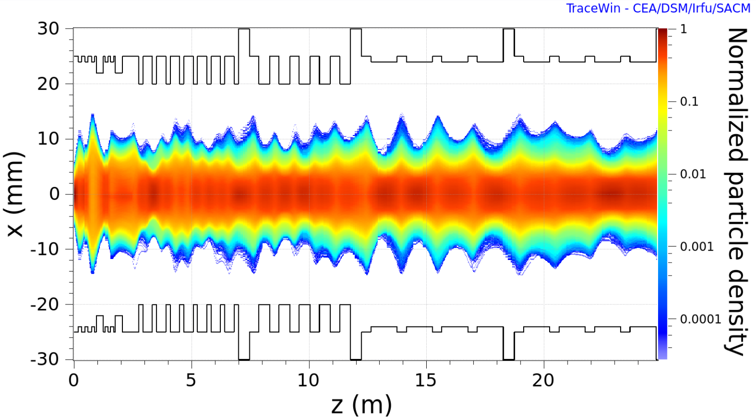
Step 35

IFMIF Linac Halo Matching



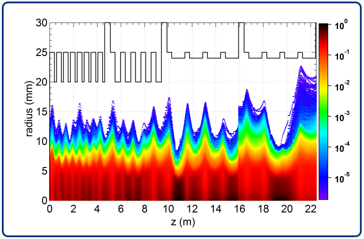
Step 45

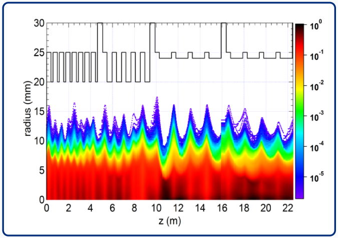
IFMIF Linac Halo Matching



Step 60

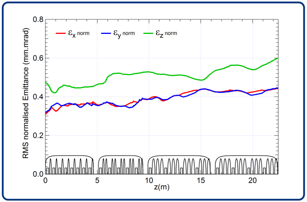
Emittance Matching vs Halo Matching

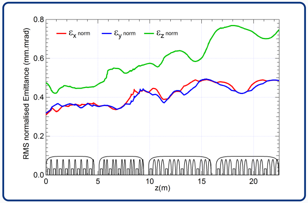




Emittance/RMS matching

Halo matching



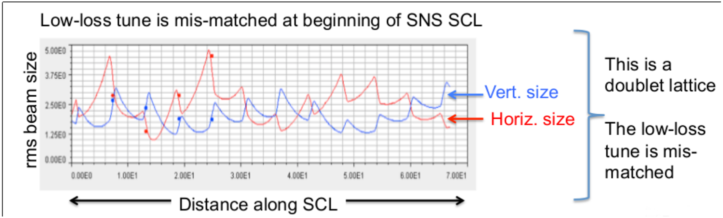


P.A.P Nghiem *et al*, Laser Part. Beams 32, 10-118 (2014).

The SNS Sxperience

"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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Micro Loss Monitor Choice

The ideal µloss monitor

- Sensitive to beam losses better than 10^{-6} of the beam power
- Fast counting rate to be used for beam tuning (several tens of seconds per each tuning step)
- Sensitive to neutrons but less to X-rays and γ produced by sc cavities
- Can be operated at 4.5K (and be stable at cryogenic temperature)
- Very good reliability (no possibility of dismounting)
- High radiation hardness
- Reasonable price

Some compromises have to be done...

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- Very good reliability (no possibility of dismounting)
- High radiation hardness
- ~~Reasonable price~~

~~Some compromises have to be done...~~

Single Crystalline CVD Diamonds can be used as µLoM

Parameter	Value
Size	$4\times4\times0.5\ \mathrm{mm}^3$
Density	$3.52\ \mathrm{g/cm}^3$
Resistivity	$10^{13} - 10^{16}\ \Omega\,\mathrm{m}$
ε_r	5.7
e^-/hole production	13.2 eV
Band-gap	5.5 eV
Radiation hardness	500 Mrad (24 GeV H^+)

J. Marroncle
(and his team)

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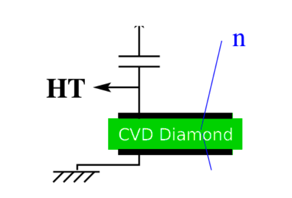
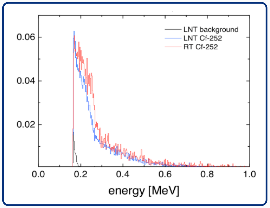


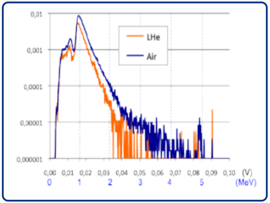
J. Marroncle
(and his team)

Tests at Cryogenic Temperature

Tests at 77 K (LN_2) in Saclay
^{252}Cf source radiating γ and fission neutrons



Tests at 4.5 K (L^4He) in Saclay
^{252}Cf source radiating γ and fission neutrons

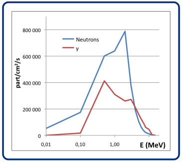


These results demonstrate the diamond ability to work at cryogenic temperature

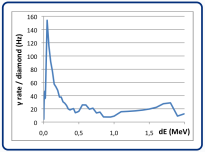
Counting Rate Estimation

Simulations

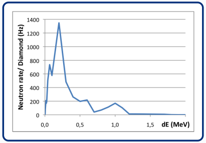
Expected counting rate were simulated for beam losses of 1 W/m in the SRF linac.



Incident *n*. and γ



n. deposited energy



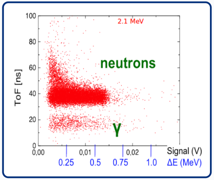
γ deposited energy

Threshold (kev)	*n* (kHz)	γ (kHz)
70	3.7	1.2
100	3.2	1.1
200	1.8	0.9
300	1.3	0.8
600	0.7	0.6

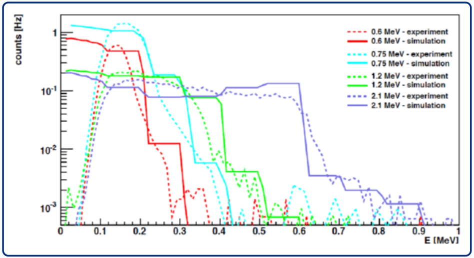
- Background coming from the beam dump should contribute, but normally < 10% of the 1W/m losses
- Even with a duty cycle of 10^{-4}, with a 200 keV threshold, still 16 counts/mn

Response of Diamond to Neutrons
Experiment

Response of diamonds to neutrons produced by a Van de Graff



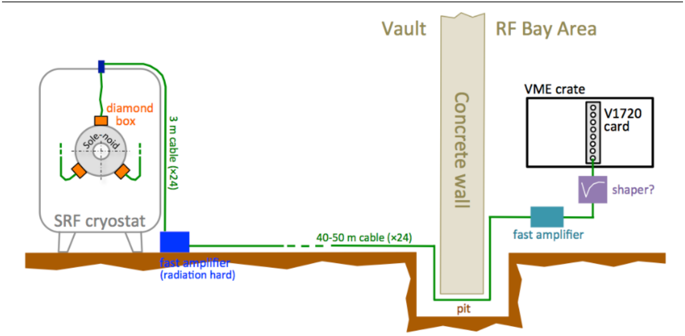
n / γ discrimination by tof



Measured and simulated energy deposition for *n*. of 0.6, 0.75, 1.2, 2.1 MeV.

- Good agreement between experiments and simulations: quite good confidence in simulated counting rates
- Missing/imprecise beam parameters for neutrons of higher energy, but low contribution to the signal

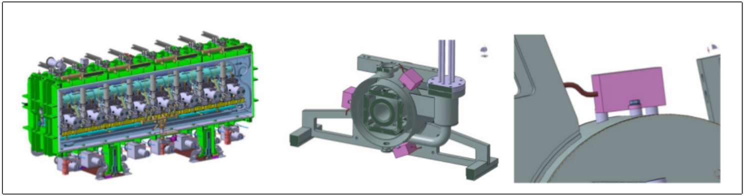
Front End Electronics



To keep a reasonable signal/noise ratio

- 1 fast amplifier close to the µLoM (radiation hardened)
- 1 fast amplifier outside the vault

µLoM Implantation in a Cryomodule



Diamond µLoM implantation in the IFMIF/LIPAc cryomodule

Three µLoM on each solenoid

- beam losses localisation
- redundancy

Conclusions

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- "Halo matching" of the IFMIF linac has been successfully simulated
- "Halo matching" has been experimentally observed and apply to reduce the losses at SNS
- µloss monitors feasibility has been demonstrated
- The µLoM are **mandatory** for IFMIF machine tuning

Remarks for discussion

- Beam dynamics matching with realistic beam diagnostics
- Is emittance conservation really mandatory ?
- Increase/improve interactions between beam physicists and diagnostics physicists

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Thank you for your attention !