



# Muon Phase Rotation and Cooling: Simulation Work at CERN

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## Work done at CERN and INFN since Nufact01

- new 88 MHz front-end
- update on cooling experiment simulations
- figure of merit for cooling performance
- simulation software (PATH)

contributions from:

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M.Migliorati, F.Tazzioli, C.Vaccarezza



## New 88 MHz Front-End

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idea: eliminate the 44 MHz section and start directly with 88 MHz

- 44 MHz cavities are bulky and difficult objects
- longitudinal acceptance of 0.1 eVs is compatible with 88 MHz
- solenoid field in the reference scenario was too conservative
- start phase rotation closer to the target, i.e. limit longitudinal emittance growth due to semi-relativistic effects
- depends on achievable gradient (will not work below 4 MV/m)



## New 88 MHz Front-End

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what made the new front-end possible

- solenoid gradients can be higher than we thought  
this is a result of the solenoid design done for the MICE study

quench limit for *NbTi* at 4.5 K: 9 T

maximum  $B_z$  on axis: 4.5 T if at 60% on load line

6.0 T if at 80% on load line

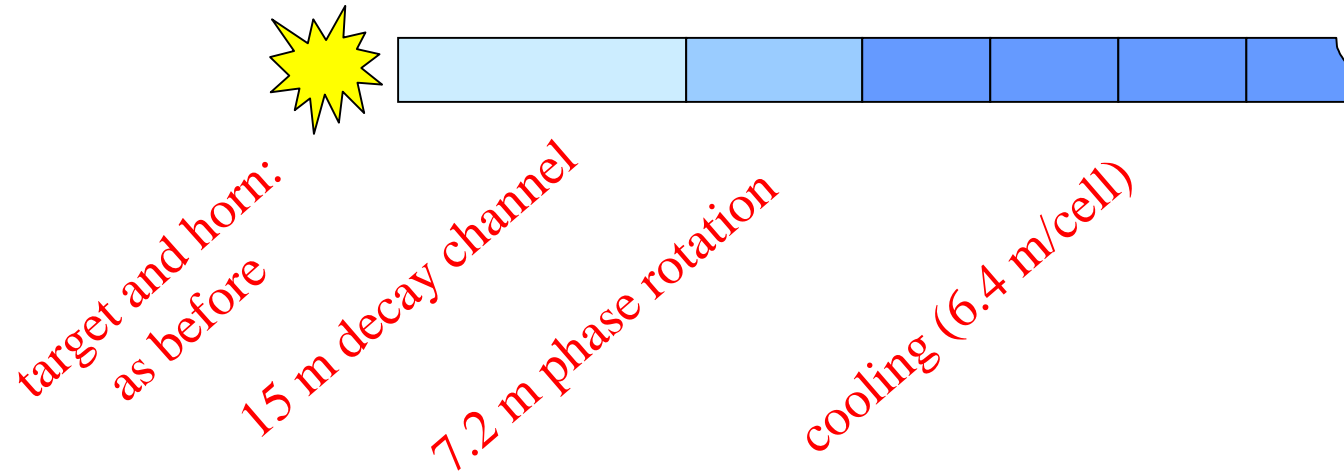
- solenoid strength of 4 T appears possible

- bore radius of 88 MHz cavities can be increased from 15 cm to 20 cm

this allows to employ 88 MHz cavities from the beginning without  
loosing too much transverse acceptance



# New 88 MHz Front-End: Lay-Out



- distribution from target as before
- 15 m solenoid decay channel at 4 T
- 7.2 m phase rotation, 8 3 88 MHz cavities (1 = 0.9 m,  $\Delta E = 3.6$  MV/cavity,  $\Phi = -90^\circ$ ) with 4 T solenoids
- cooling modules (10 – 20)  
1 module: 6 cavities (88 MHz,  $\Phi = 0^\circ$ ), 0.5 m LH absorber, 0.5 m matching solenoid
- optional: second stage cooling channel with quadrupoles



# New 88 MHz Front-End: Lay-Out

<b>80 MHz</b>	<b>Decay</b>	<b>Rotation</b>	<b>Cooling I</b>	<b>Acceleration I</b>	<b>Acceleration II</b>
<b>Length [m]</b>	<b>15</b>	<b>8</b>	<b>90</b>	<b>≈ 10</b>	<b>≈ 450</b>
<b>Diameter [cm]</b>	<b>40</b>	<b>40</b>	<b>40</b>	<b>30</b>	<b>20</b>
<b>B-field [T]</b>	<b>4</b>	<b>4</b>	<b>4</b>	<b>4</b>	<b>quads</b>
<b>Frequency [MHz]</b>		<b>80</b>	<b>80</b>	<b>80</b>	<b>80-200</b>
<b>Gradient [MV/m]</b>		<b>4</b>	<b>4</b>	<b>4</b>	<b>4-10</b>
<b>Kin Energy [MeV]</b>		<b>200</b>	<b>200</b>	<b>300</b>	<b>2000</b>

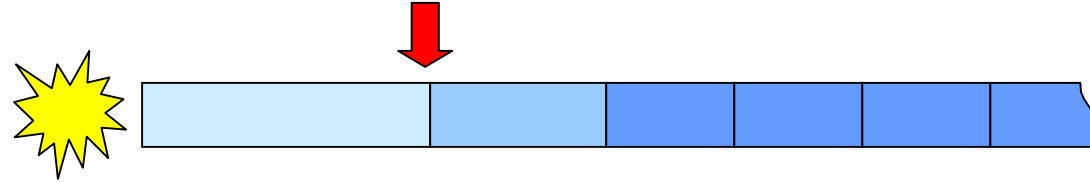
fields: hard-edge equivalent; gradient: average

options: have  $r = 20$  cm in first part of cooling channel, then  $r = 15$  cm

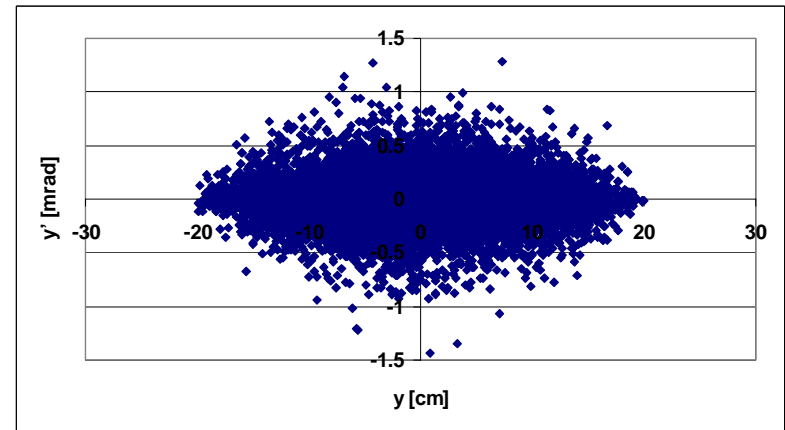
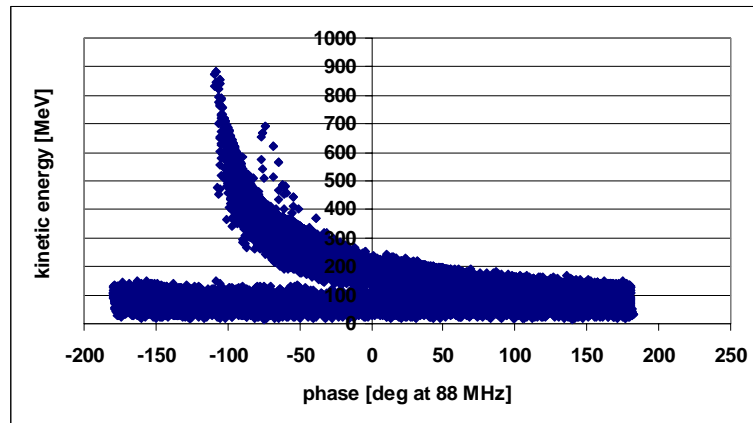
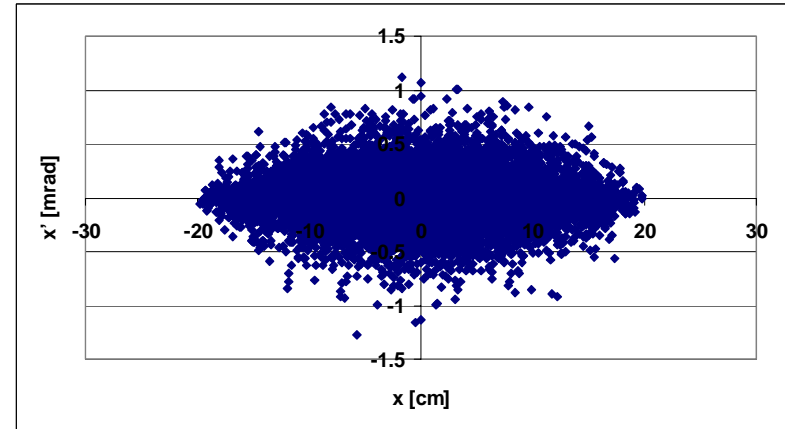
quadrupole channel: no coupling, but acceptance is only twice RLA acceptance (presently: 5 times RLA acceptance!)



# New 88 MHz Front-End: Decay Channel

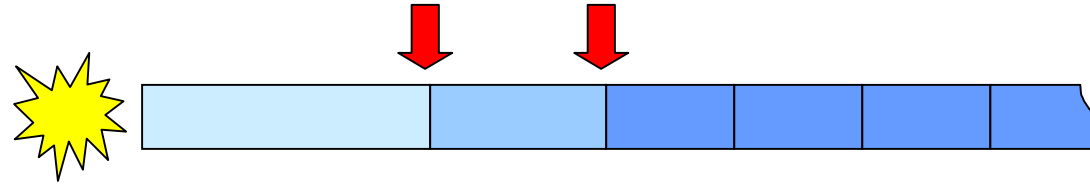


15 m decay channel

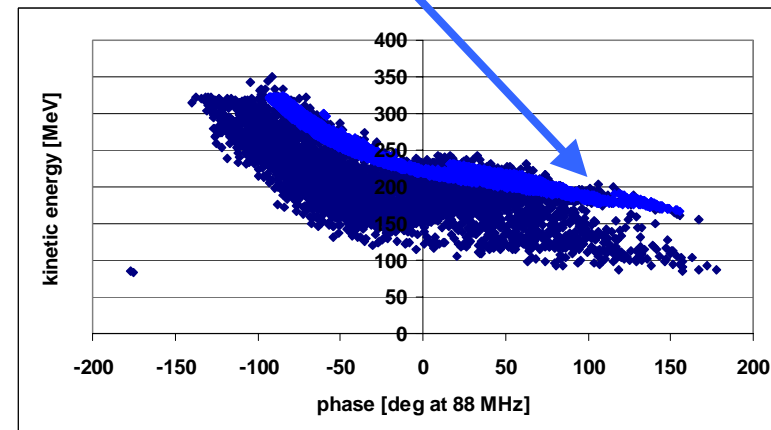
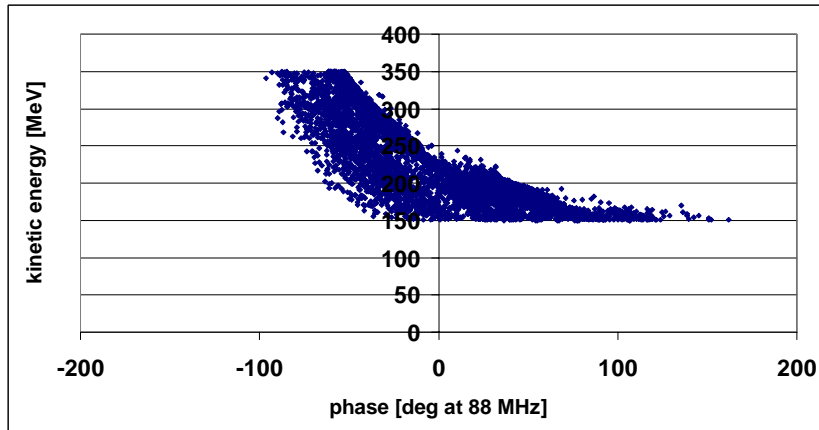




# New 88 MHz Front-End: Phase Rotation

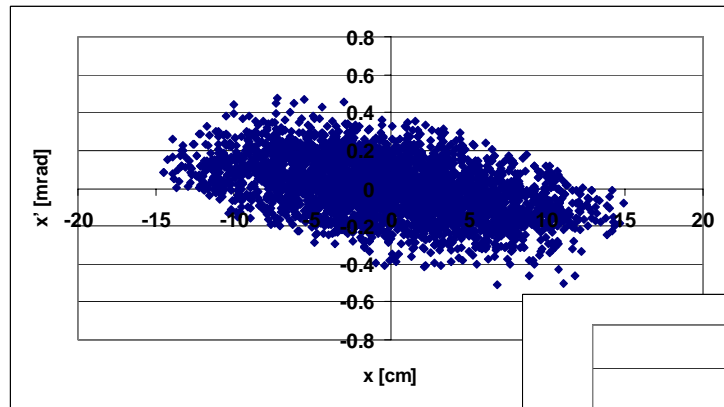
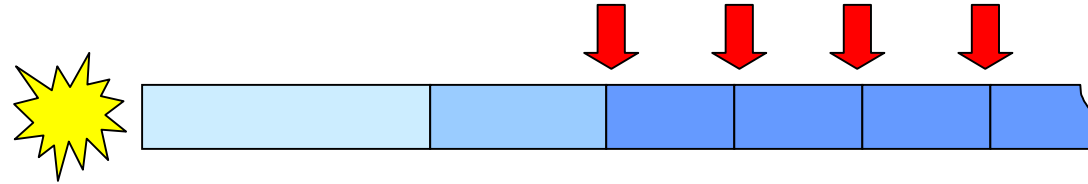


7.2 m phase rotation



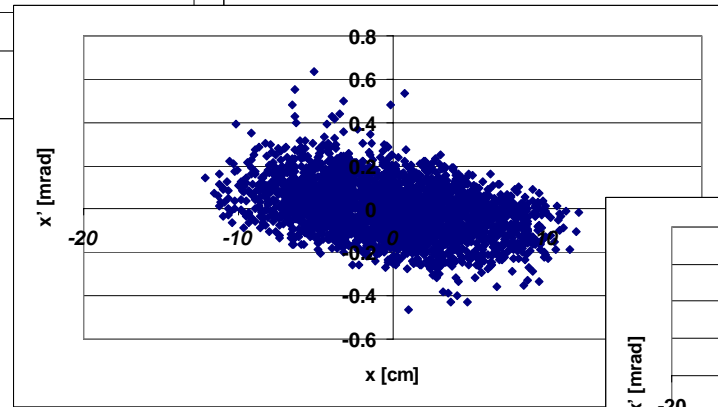


# New 88 MHz Front-End: Cooling



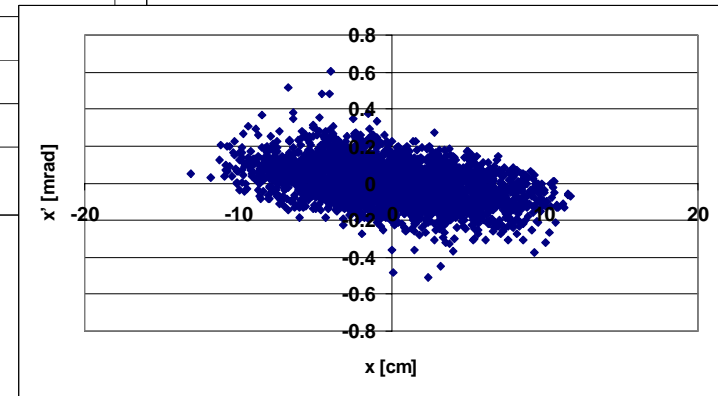
input

cooling (6.4 m/cell)



cell 5

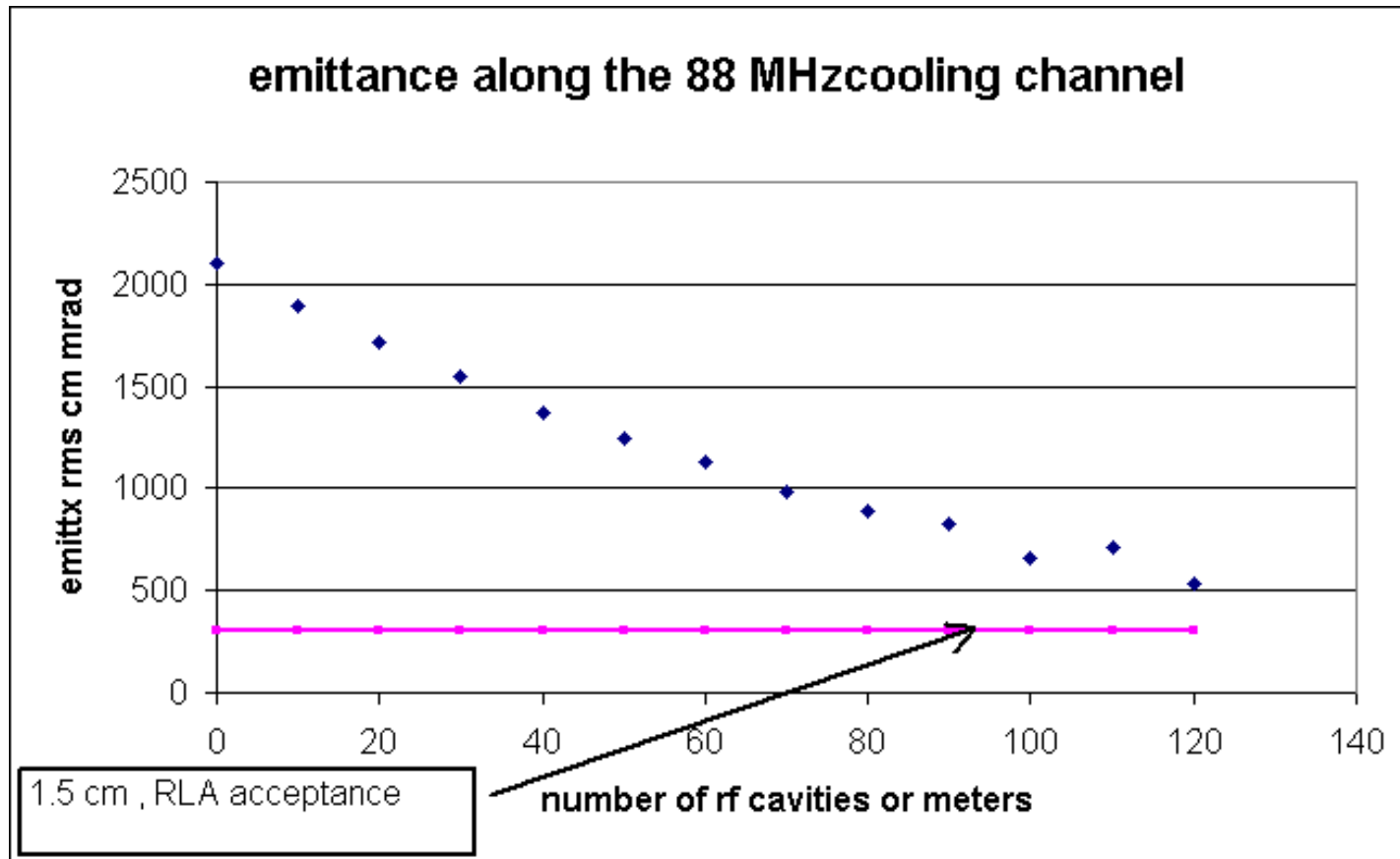
cell 10





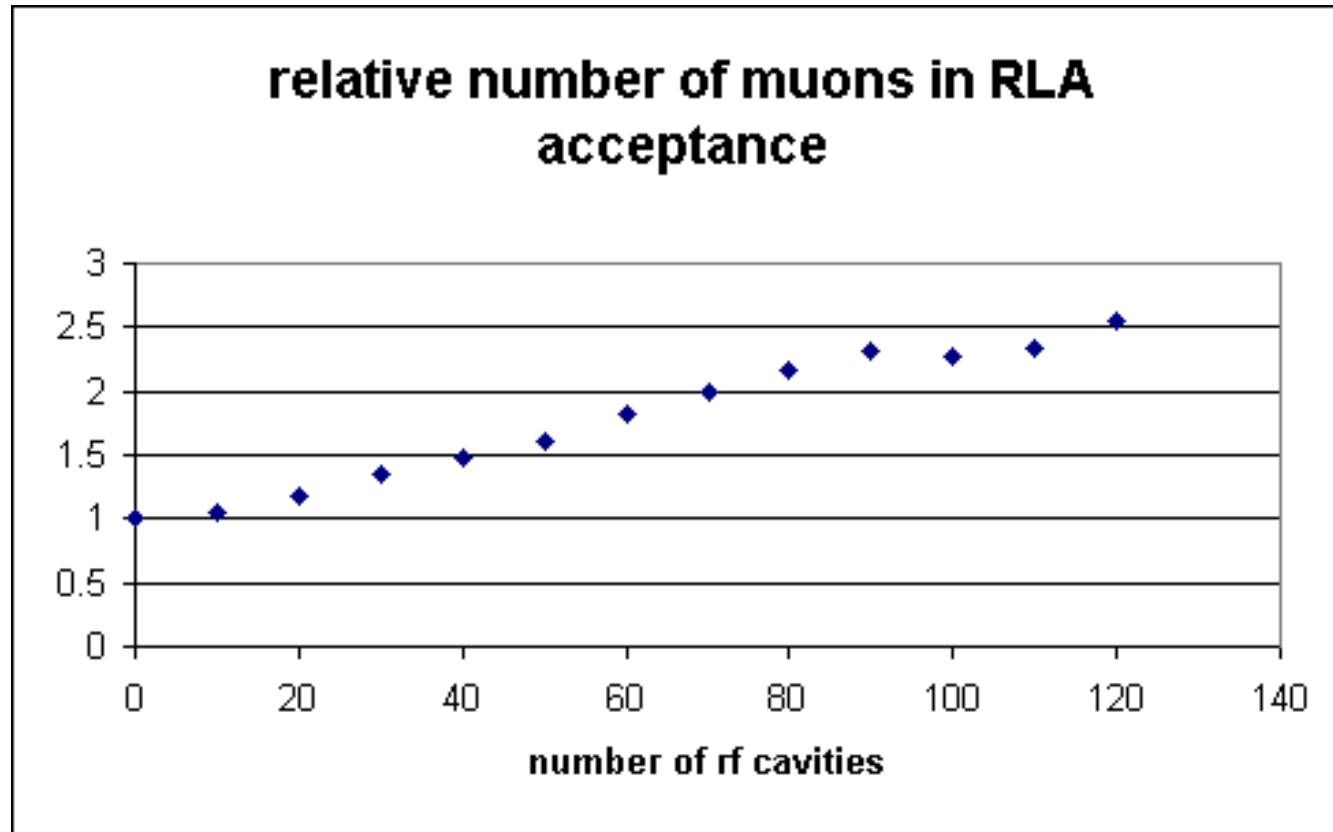


# New 88 MHz Front-End: Cooling Performance





# New 88 MHz Front-End: Cooling Performance



cooling efficiency is comparable to present 44/88 MHz channel



# Cooling Experiment Simulations

two options studied:

a) 88 MHz (4 cavities and 8 cavities, 4 MV/m)

work done at CERN: optimisation, tracking through field maps  
(note the equivalence of hard-edge and field map model),  
parameter scan

b) 200 MHz (4 cells at 7.6 MV/m)

work done at INFN Frascati in collaboration with CERN

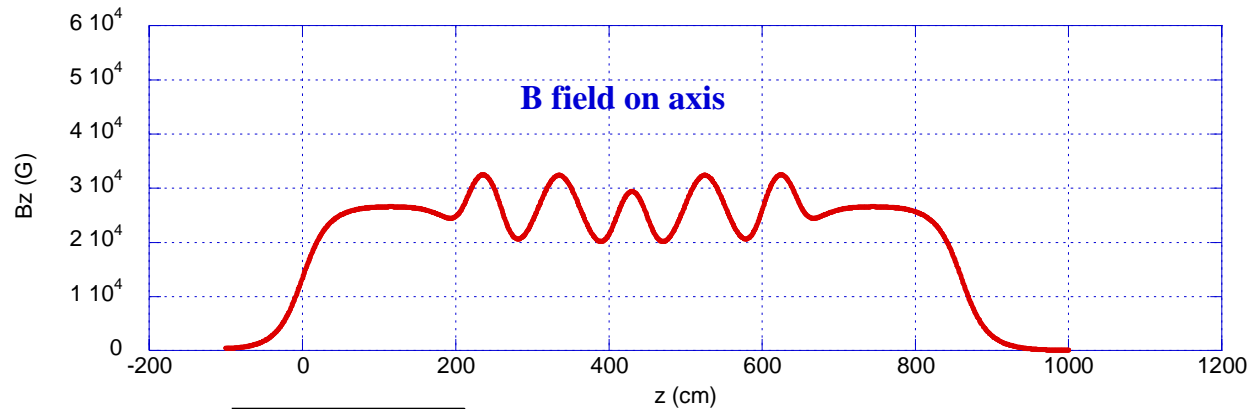
cooling efficiency comparable – solenoid arrangement very different!  
(88 MHz option shows less coupling than 200 MHz option)

see CERN NUFACT Notes 90, 108 and EPAC 2002

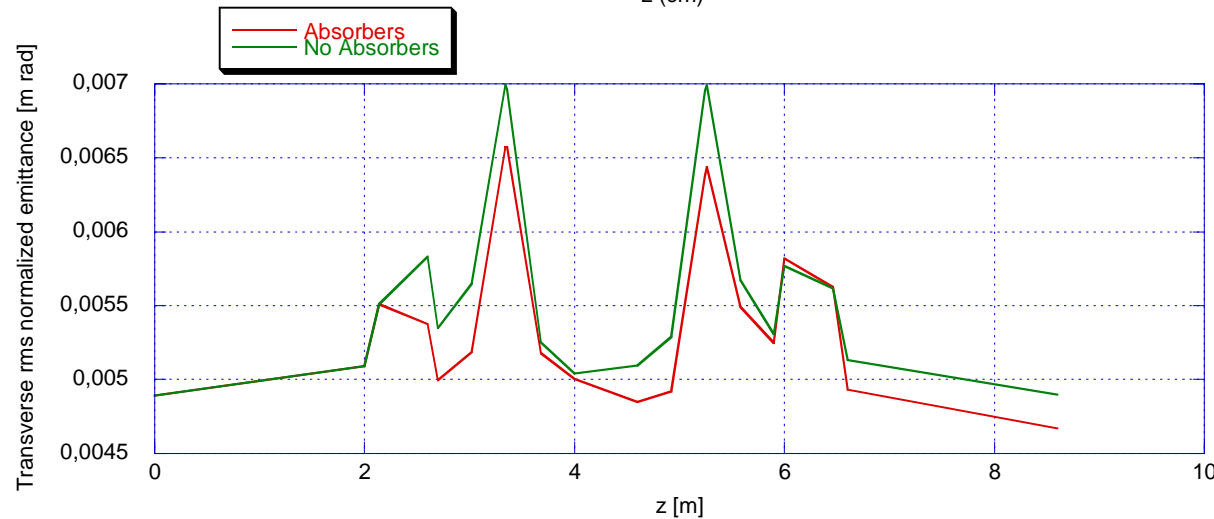


# 200 MHz Option: PATH Simulation

M.Migliorati, C.Vaccarezza, F.Tazzioli (INFN Frascati)



particle gain in acceptance:  
**+ 9%**  
as in 88 MHz case



**PATH simulation of  $2 \times 2$  cell 200 MHz cavity with  $2 \times 46$  cm LH absorber**



# Cooling Experiment: Figure of Merit

- Cooling channel: increase the number of muons in the acceptance of the following accelerators and the decay ring (3 planes independently).
- Solenoidal optics: inter-plane coupling depending on lattice and z-position.
- To measure cooling performance in the presence of coupling (i.e. along the cooling experiment):

→ Algorithm to count particles in 4D/6D acceptance hyperellipsoids. Measure 4D/6D cooling rather than 2D projections.

Orientation of the ellipsoid adapted to muon distribution to maximize counts.

**Condition for counting particles in  $k$  dimensional hyperellipsoids:**

$$X_0^T \Sigma^{-1} X_0 \leq \left( \frac{\mathcal{E}_{\text{acceptance}}}{\mathcal{E}_{\text{rms}}} \right)^{2/k}$$

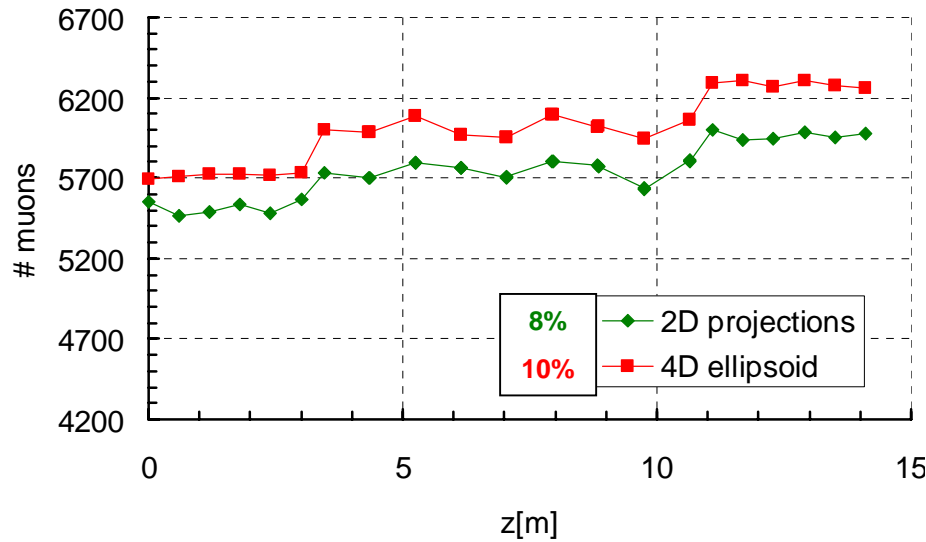
$X_0$  ... coordinate vector of the particle

$\Sigma$  ... beam sigma matrix



# Cooling Experiment: Figure of Merit

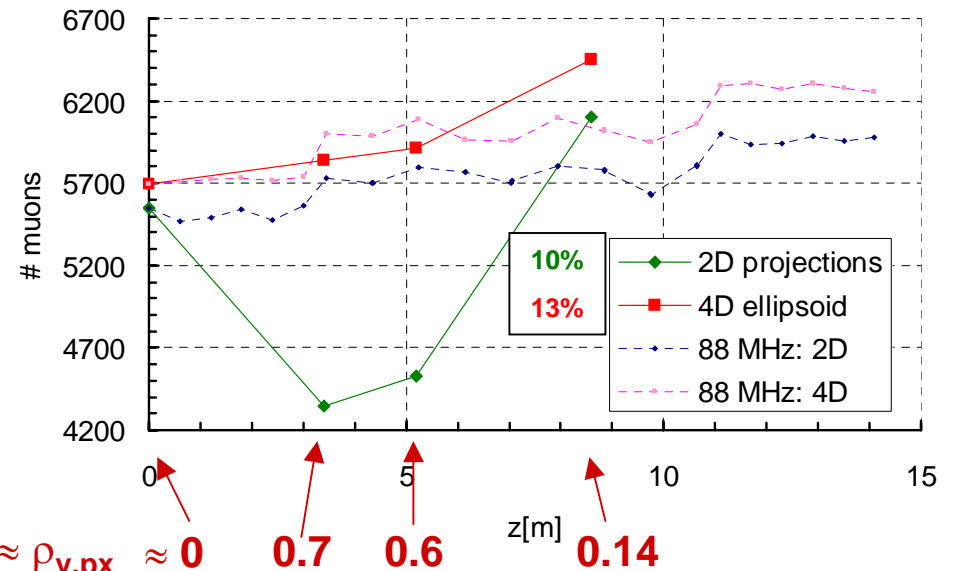
88 MHz cooling experiment  
counting muons inside a 4D volume of  $(0.015 \pi \text{ m rad})^2$



**Correlation:**  $\rho_{x,py} \approx \rho_{y,px} \leq 0.08$

**Follow the cooling performance along the z-position in the presence of correlations**

200 MHz cooling experiment  
counting muons inside a 4D volume of  $(0.015 \pi \text{ m rad})^2$



**Correlation:**  $\rho_{x,py} \approx \rho_{y,px} \approx 0$    **0.7**   **0.6**   **0.14**



# Simulation Code PATH: User Interface

The screenshot shows the PATH Manager software interface. The main window contains several diagnostic and absorber components. A 'Graphical Output' window is open, displaying a scatter plot of particles in the X-Y plane. The plot shows a dense cluster of red dots centered around X=0 and Y=0. The axes are labeled 'X [m] x 10E-2' and 'Y [m] x 10E-2'. To the right of the plot, there are statistics for the loaded beams and field maps.

**Graphical Output Statistics:**

- Number Loaded : 0
- $\alpha$  :  $-2.226782E-3$
- $\beta$  :  $1.097645E-6$
- H Center :  $3.659246E-4$
- V Center :  $6.58657E-4$
- Title
- Total :  $7.954579E-2$
- 35.4% :  $3.082023E-2$
- 90.8% :  $3.248241E-2$
- 68.3% :  $2.031609E-2$
- RMS :  $7.963766E-3$

**Calculations Output:**

```
> 3:41: - START A NEW RUN
> Running device 0 (Beamen : muongeneration)
> BEAM GENERATION
- BINOMIAL DISTRIBUTION WITH
M(z) = 1.000000000000000
M(z) = 1.000000000000000

- RMS ELLIPSE EXTENSIONS :
X [m] : -0.9486832980505140-001 TO 0.9486832980505140-001
X [rad] : -0.9486832980505140-001 TO 0.9486832980505140-001
Y [m] : -0.9486832980505140-001 TO 0.9486832980505140-001
Y [rad] : -0.9486832980505140-001 TO 0.9486832980505140-001
d[Hz] [deg] : -22.499999999999991 TO 22.499999999999991
P [GeV/c] : 0.276134365517948 TO 0.297450035098034
E [GeV] : 0.1900000000000000 TO 0.2100000000000000

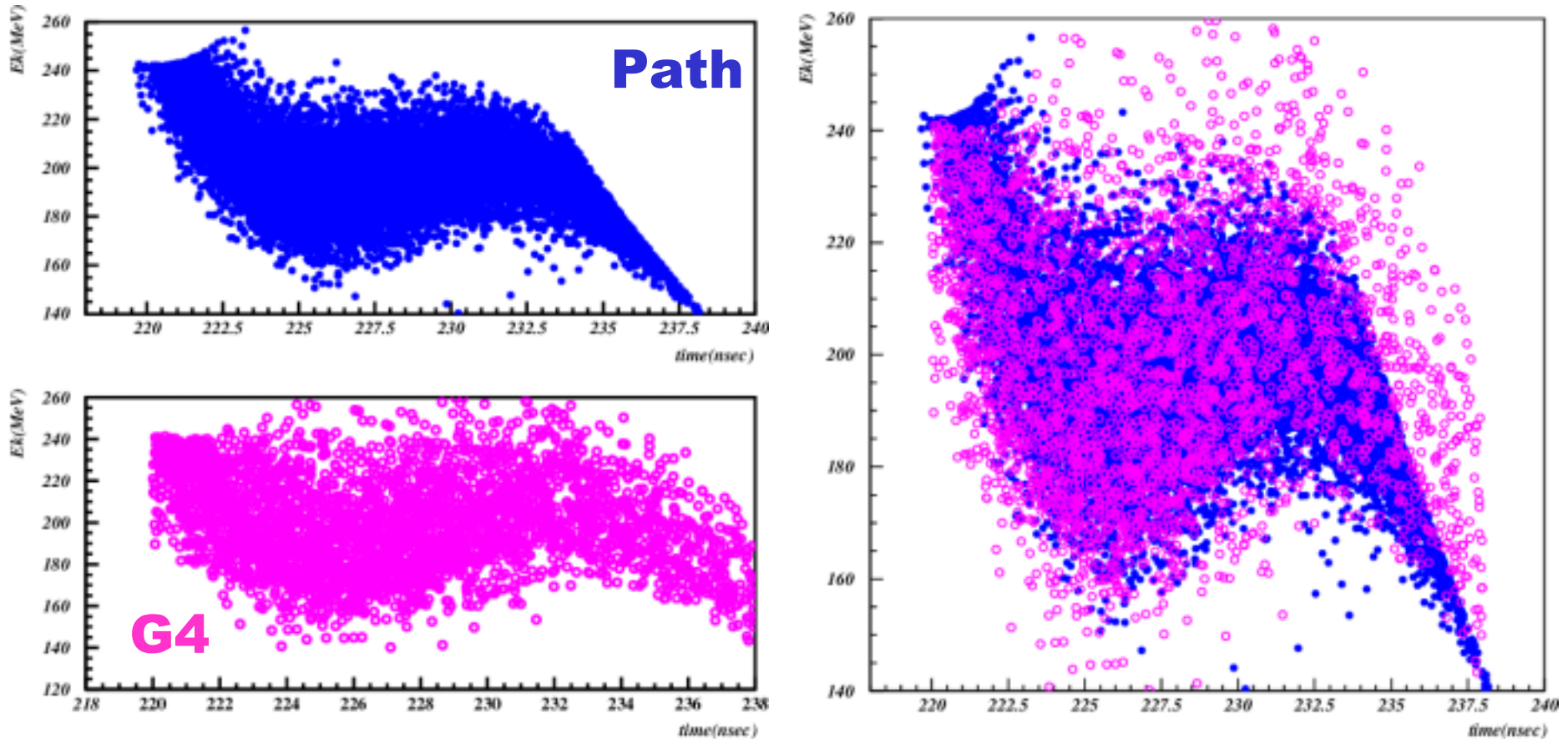
> Running device 1 (MappedField : diagnostic)
> 15:41 - DEVICE 1 : [R,Z,B[R,Z]]_FIELD_MAP

Project Output
> 2:17: - OPENING DAT file C:\Program Files\PATH Manager\My
Projects\ACAN\HAI\3\Beams\Frme 24 - diagnostic1.dat for input
* Line frequency is 88 MHz
* Memory (re)allocated for 10000 particles
* All Done
> 2:17: - END PROJECT LOADING
```

25 beams loaded (17.166 Mbytes) / 2 field maps loaded (490.25 Kbytes) 5/27/2002 2:17 PM



# Simulation Code PATH: Cross Check vs GEANT4

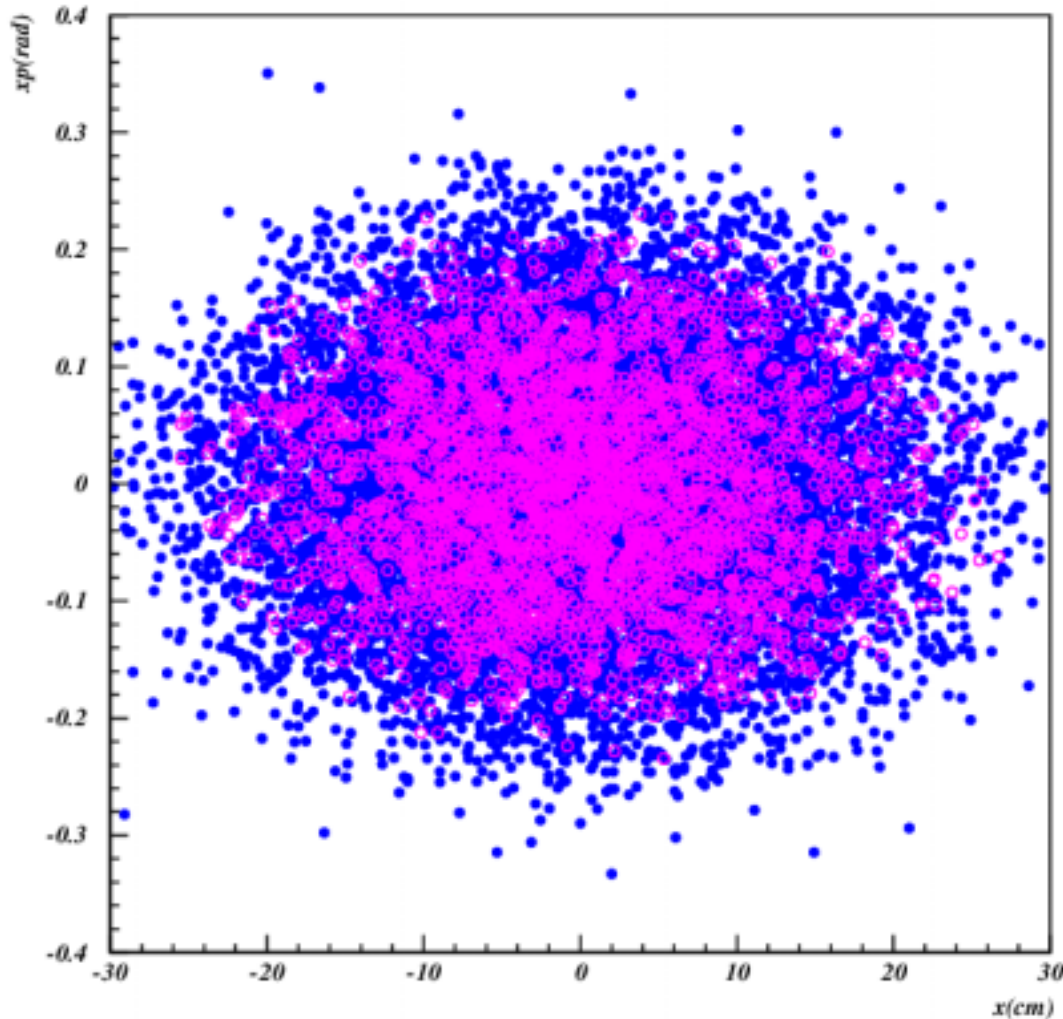


simulation of the phase rotation in the CERN cooling channel with PATH and GEANT4  
remaining discrepancies: rf tuning, not exactly the same channel





# Simulation Code PATH: Cross Check vs GEANT4



## transverse plane:

small discrepancy due to particle dynamics in solenoid channel

## overall comparison result:

- muons at input:    PATH 15222  
                                 G4     4560
- transmission:     PATH 100%  
                                 G4     94%

see CERN NF Note 102



## Summary

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- new 88 MHz front-end designed
- cooling experiment at 88 MHz: study finished and documented (NF Note 108)
- cooling experiment at 200 MHz: study finished and documented (NF Note 108 and EPAC2002)
- figure of merit for cooling experiment and cooling channel studied
- PATH/GEANT comparison: very good agreement