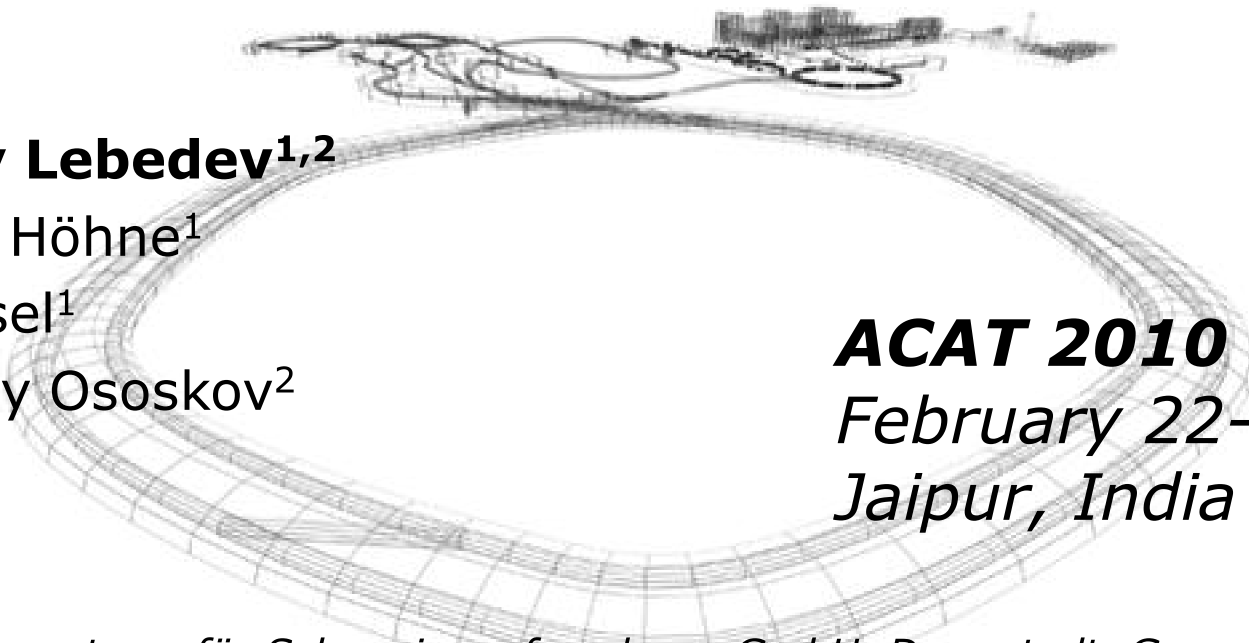
Fast parallel tracking algorithm for the muon detector of the CBM experiment at FAIR



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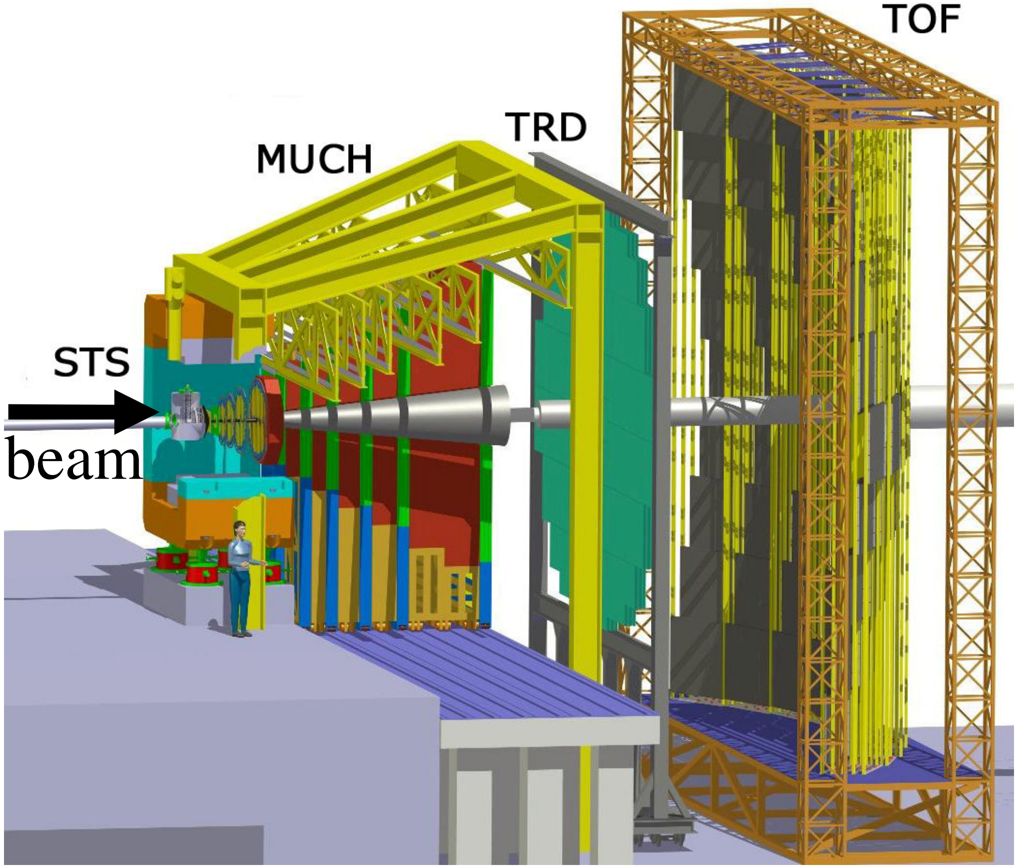
The CBM experiment at FAIR



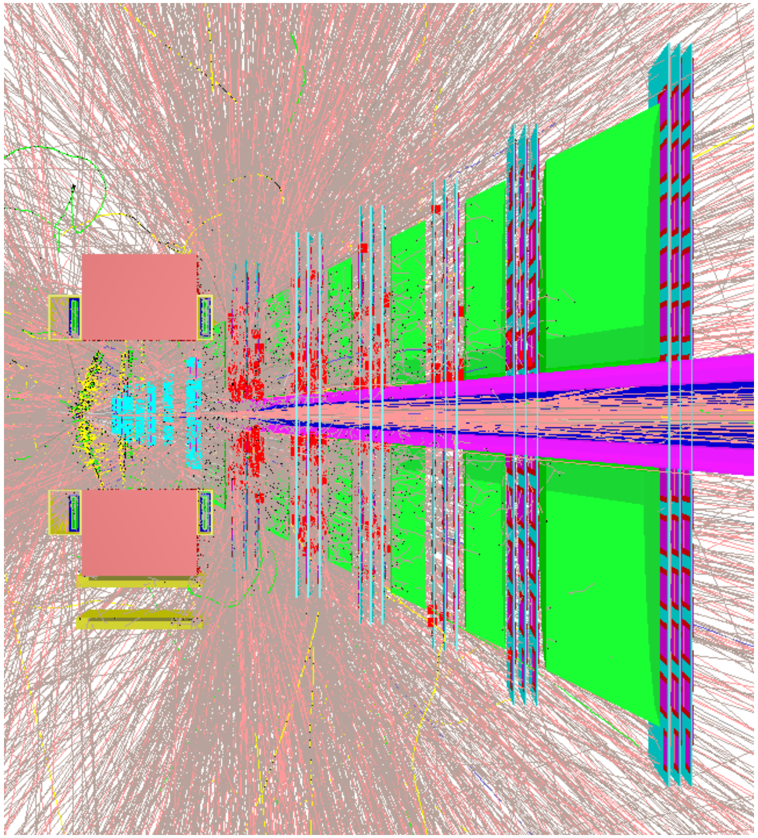
STS	track, vertex and momentum reconstruction
MUCH	muon identification
TRD	in case of muons only tracking
TOF	time of flight measurement

- exploration of the QCD phase diagram in regions of high baryon densities and moderate temperatures.
- comprehensive measurement of hadron and lepton production in pp, pA and AA collisions for 8-45 AGeV beam energy
- fixed target experiment

Challenges for tracking

Peculiarities for CBM:

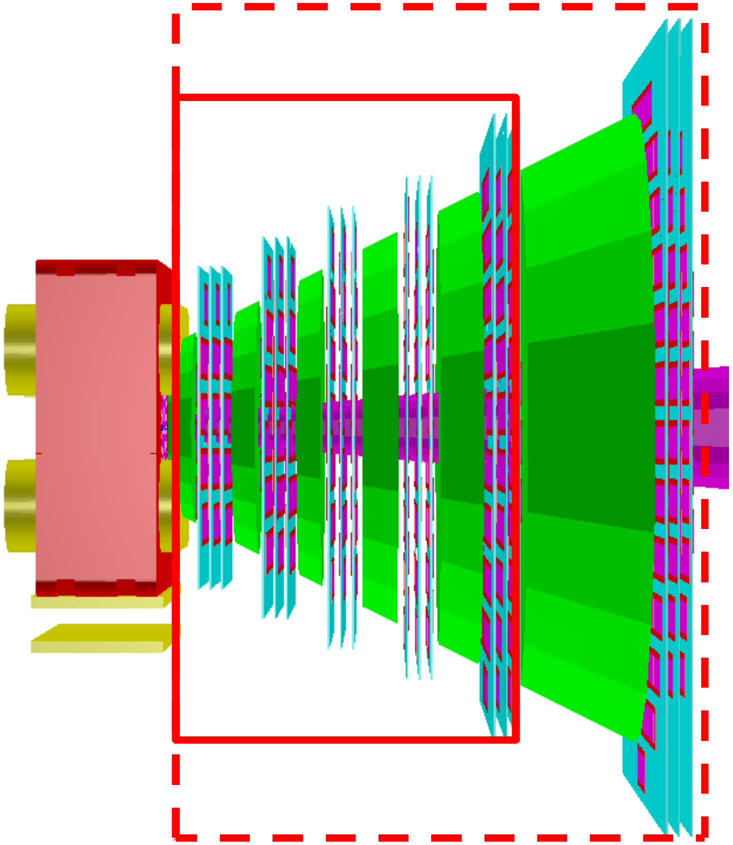
- large track multiplicities
  - up to **800** charged particles per reaction in +/- 25°
- high reaction rate
  - up to **10 MHz**
- measurement of rare probes → need for fast and efficient trigger algorithms
- high hit density
- large material budget – especially in the muon detector
- complex detector structure, overlapping sensors, dead zones
- enormous amount of data: foreseen are currently 1Gb/s archiving rate (600Tb/week)



Central Au+Au collision at 25 *A*GeV (UrQMD + GEANT3)

→ **fast tracking algorithms are essential**

The Muon detector (MUCH)



Choose alternating detector-absorber layout for continuos tracking of the muons through the absorber

Measurements of:

Low mass vector mesons
5 Fe absorbers (**125 cm**)
7.5 λ_I, p> 1.5 GeV/c

Charmonium
6 Fe absorbers (**225 cm**)
13.5 λ_I, p> 2.8 GeV/c

3 detector stations between the absorbers

Detector challenges:

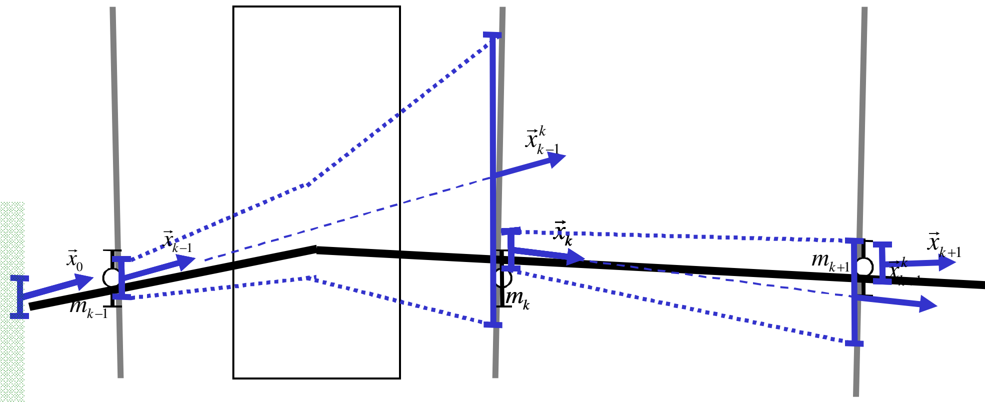
- High hit density (up to 1 hit per cm^2 per event)
- High event rates (10^7 events/s)
- Position resolution < 300 μm

→ use pad readout (e.g. GEMs), minimum pad size $2.8x2.8\ mm^2$.
→ for the last stations **straw tubes** are under investigation

Track reconstruction algorithm

Two main steps:

- **Tracking**
- **Global track selection**



Tracking is based on

- Track following
- Initial seeds are tracks reconstructed in the STS (fast Cellular Automaton (CA), I.Kisel)
- Kalman Filter
- Validation gate
- Hit-to-track association techniques
  - **nearest neighbor:** attaches the closest hit from the validation gate

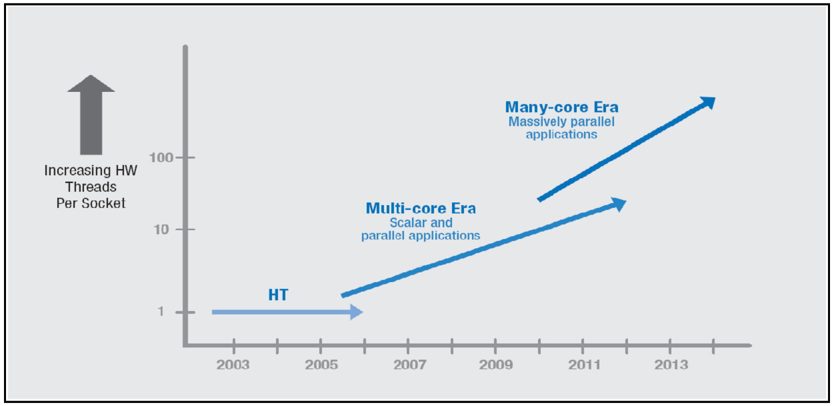
Global track selection

- aim: remove clone and ghost tracks
- tracks are sorted by their quality, obtained by chi-square and track length
- Check for shared hits

Track propagation

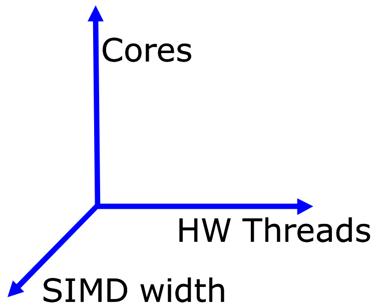
- *Inhomogeneous magnetic field:*
  - solution of the equation of motion with the 4th order Runge-Kutta method
- *Large material budget:*
  - Energy loss (ionization: Bethe-Bloch, bremsstrahlung: Bethe-Heitler, pair production)
  - Multiple scattering (Gaussian approximation)

Parallelism

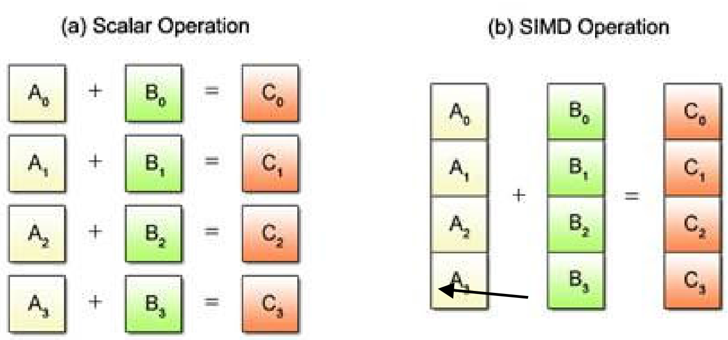


S. Borkar et al. (Intel), "Platform 2015: Intel Platform Evolution for the Next Decade", 2005.

- We´re already at the age of parallel computing
- Parallel computing relies on parallel hardware
- Parallel computing needs parallel software
- So parallel programming is very important
  - new way of thinking
  - identification of parallelism
  - design of parallel algorithm
  - implementation can be a challenge



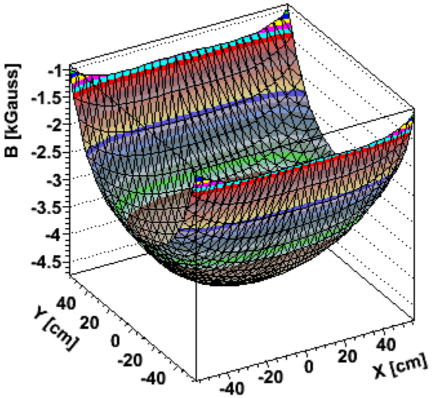
- SIMD – Single Instruction Multiple Data
  - CPU’s have it!
  - **Today**: SSE - 128 bit registers
    - 4 x float
  - **Future**: AVX, LRB
    - AVX: 8 x float
    - LRB: 16 x float
  - Benefits:
    - X time more operations per cycle
    - X time more memory throughoutput
- Multithreading
  - Many core era coming soon…
  - Tool for CPU: Threading Building Blocks

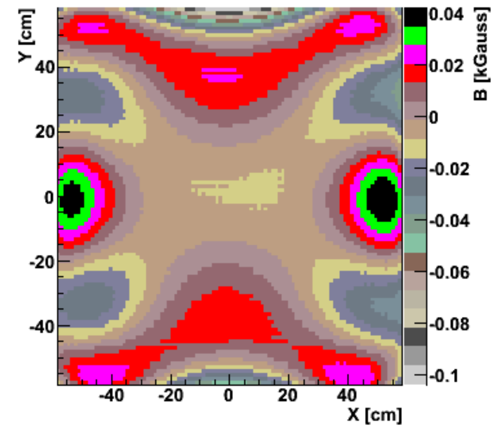


4 concurrent add operations

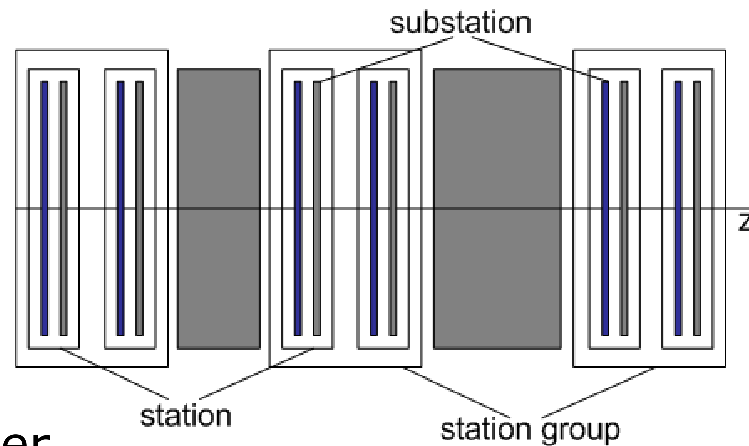
Optimization of the algorithm

- Minimize access to global memory
  - Approximation of the 70 MB large magnetic field map
    - 5 degree polynomial in the detector planes
    - parabola between the stations





- Simplification of the detector geometry
  - Problem
    - Monte-Carlo geometry consists of 800000 nodes
    - Geometry navigation based on ROOT TGeo
  - Solution
    - Create simplified geometry by converting Monte-Carlo geometry
    - Implement fast geometry navigation for the simplified geometry



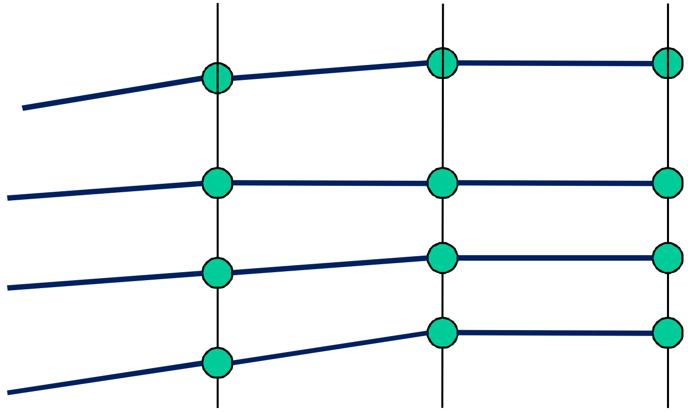
- Computational optimization of the Kalman Filter
  - From **double** to **float**
  - Implicit calculation on non-trivial matrix elements
  - Loop unrolling
  - Branches (`if then else` ..) have been eliminated

All these steps are necessary to implement SIMD tracking

SIMDization of the track fitter

- Vectorization of the tracking data
  - X_{vector} contains (X_0, X_1, X_2, X_3)
- Vectorization of the track fitter algorithm
  - SSE instructions were overwritten in a header file
- All tracks are independent and fitted by the same algorithm: 4 tracks packed into one vector and fitted in parallel

Finally SIMD version of the track fitter can fit 4 tracks at a time!



Serial tracking

Initial serial scalar version

```
for (nofTrackSeeds)
    Follow each track through the detector
    Pick up nearest hits
end for (nofTrackSeeds)
```

Can not be directly used in SIMD approach, so it has to be significantly restructured!

Parallel tracking

```
for (station groups)
    parallel_for (nofTracks/4)
        PackTrackParameters
        SIMDPropagateThroughAbsorber
    end parallel_for (nofTracks/4)
    for (stations)
        parallel_for (nofTracks/4)
            PackTrackParameters
            SIMDPropagateToStation
            AddHitToTrack
        end parallel_for (nofTracks/4)
    end for (stations)
end for (station groups)
```

Parallel loop (parallel_for over nofTracks/4, inside the station-groups loop)

Parallel loop (parallel_for over nofTracks/4, inside the stations loop)

Performance of the track fit

Track fit quality

Residuals					Pulls				
X [cm]	Y [cm]	Tx $*10^{-3}$	Ty $*10^{-3}$	q/p $*10^{-3}$ [GeV^{-1}]	X	Y	Tx	Ty	q/p
0.38	**0.39**	**9.1**	**8.7**	**3.4**	**1.02**	**0.99**	**1.08**	**1.08**	**0.92**

Speedup of the track fitter

	Time [μs/track]	Speedup
Initial	**1200**	**-**
Optimization	**13**	**92**
SIMDization	**4.4**	**3**
Multithreading	**0.5**	**8.8**
Final	**0.5**	**2400**

Throughput: $2*10^6$ tracks/s

Computer with 2xCPUs Intel Core i7 (8 cores in total) at 2.67 GHz

Performance of the parallel tracking

Simulation:

• 1000 UrQMD events at 25 AGeV Au-Au collisions + 5 μ+ and 5 μ- embedded in each event

	Initial version	Parallel version
Efficiency [%]	**94.7**	**94.0**

Speedup of the track finder

	Time [ms/event]	Speedup
Initial	**730**	**-**
Optimization	**7.2**	**101**
SIMDization	**4.8**	**1.5**
Multithreading	**1.5**	**3.3**
Final	**1.5**	**487**

Computer with 2xCPUs Intel Core i7 (8 cores in total) at 2.67 GHz

Summary

- fast reconstruction algorithms are essential!
- succesful demonstration that tracking in the muon detector is feasible in a high track density environment:
  - 95% tracking efficiency for muons passing the absorber
  - low rate of ghosts, clones and track mismatches
- Considerable optimization and parallelization of the algorithms allows to achieve a speed up factor of 2400 for the track fit and a factor 487 for the track finder
- All algorithms were implemented and tested in the CBMROOT framework and are intensivly used by CBM physicists

→ use established tracking routines for layout optimization

→ Investigate new parallel languages (CUDA, OpenCL)