Performance evaluation of a crystal-enhanced collimation system for the LHC

Valentina Previtali

R. Assman, C. Bracco, I. Yazynin, S. Redaelli, T. Weiler

outline

- LHC and its collimation system
- How a bent crystal works
- How could a crystal help the LHC?
- LHC crystal-enhanced collimation system: simulation results
- Conclusions, outlook

The Large Hadron Collider (LHC)

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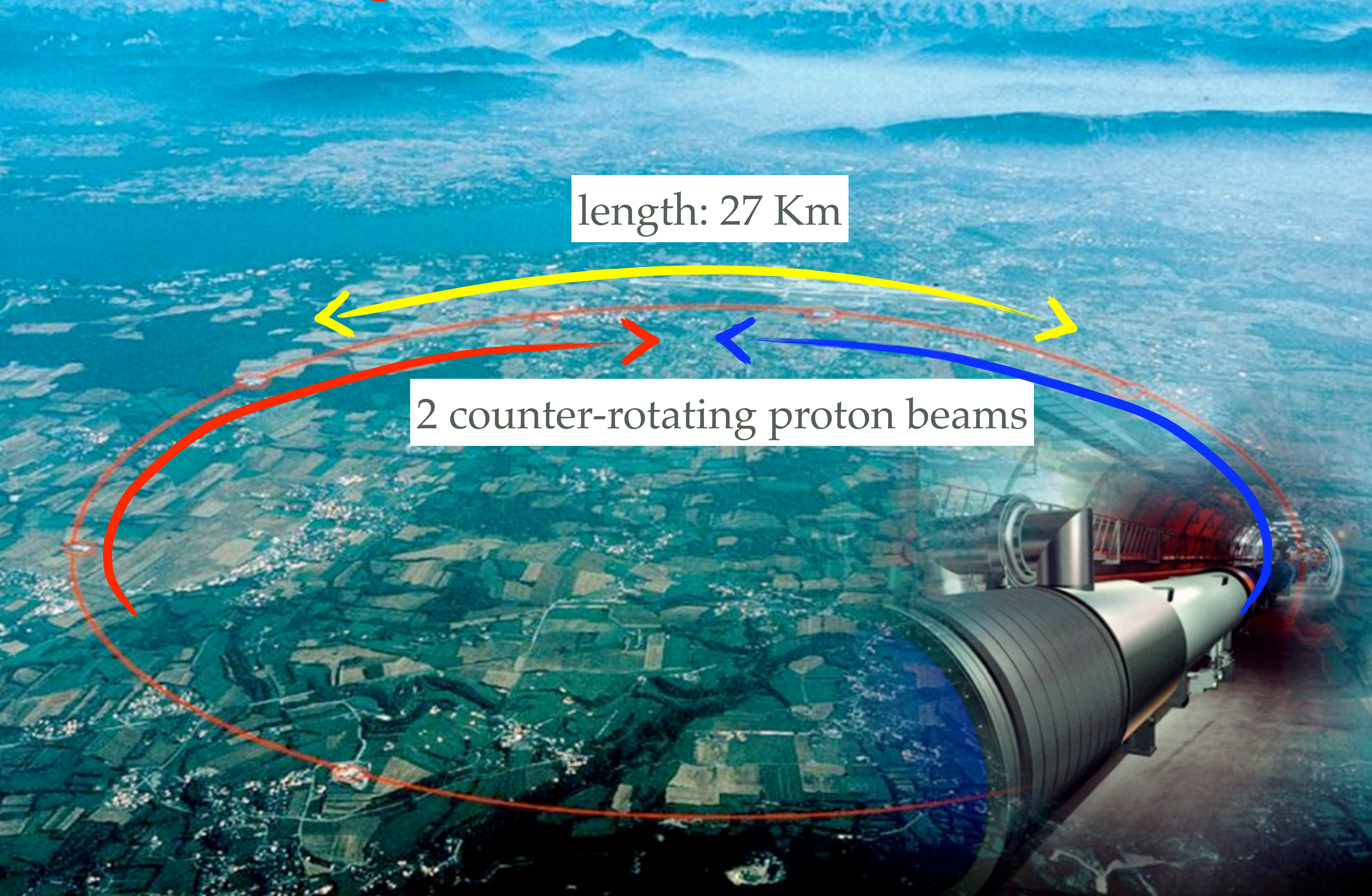

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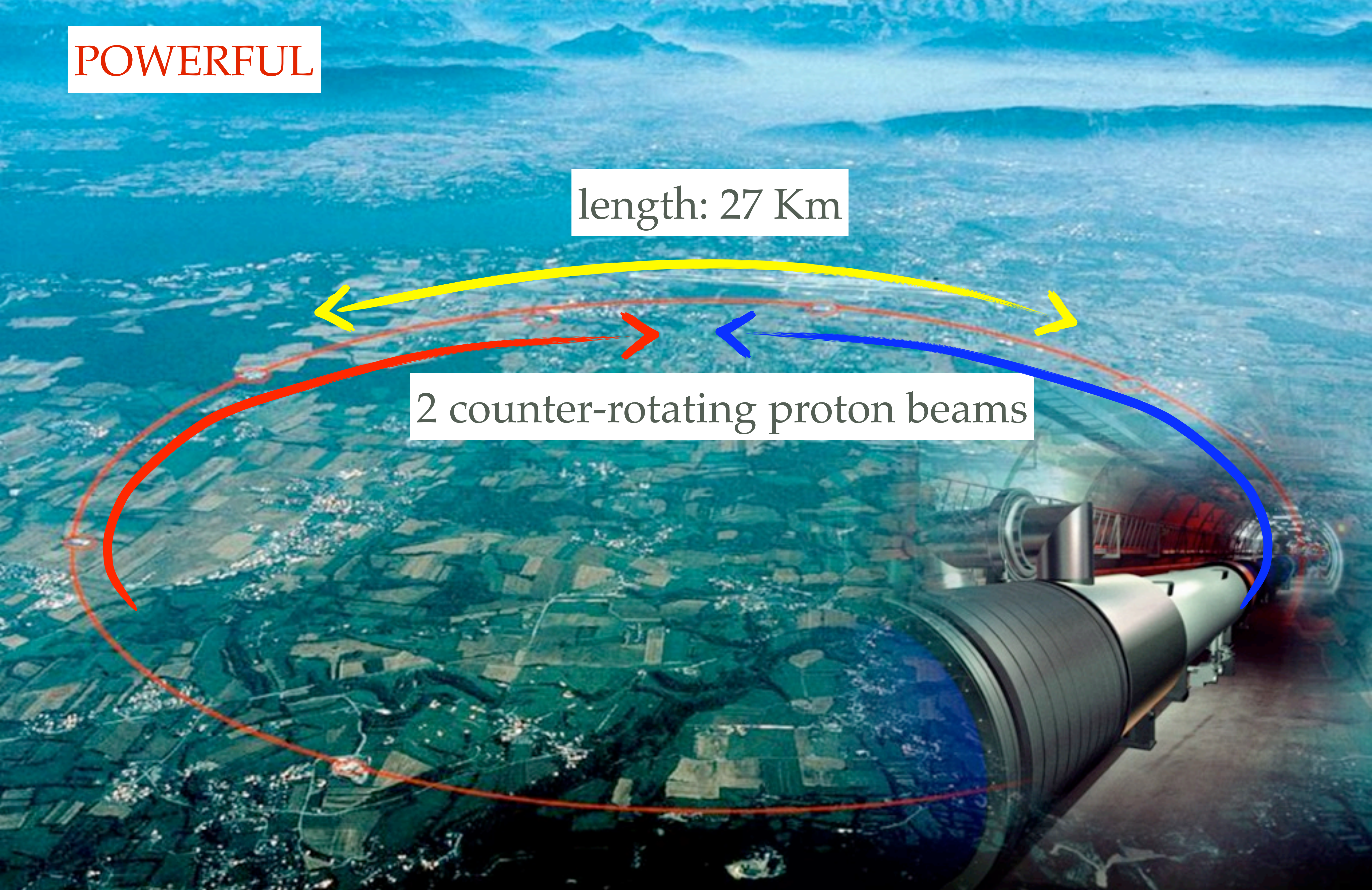
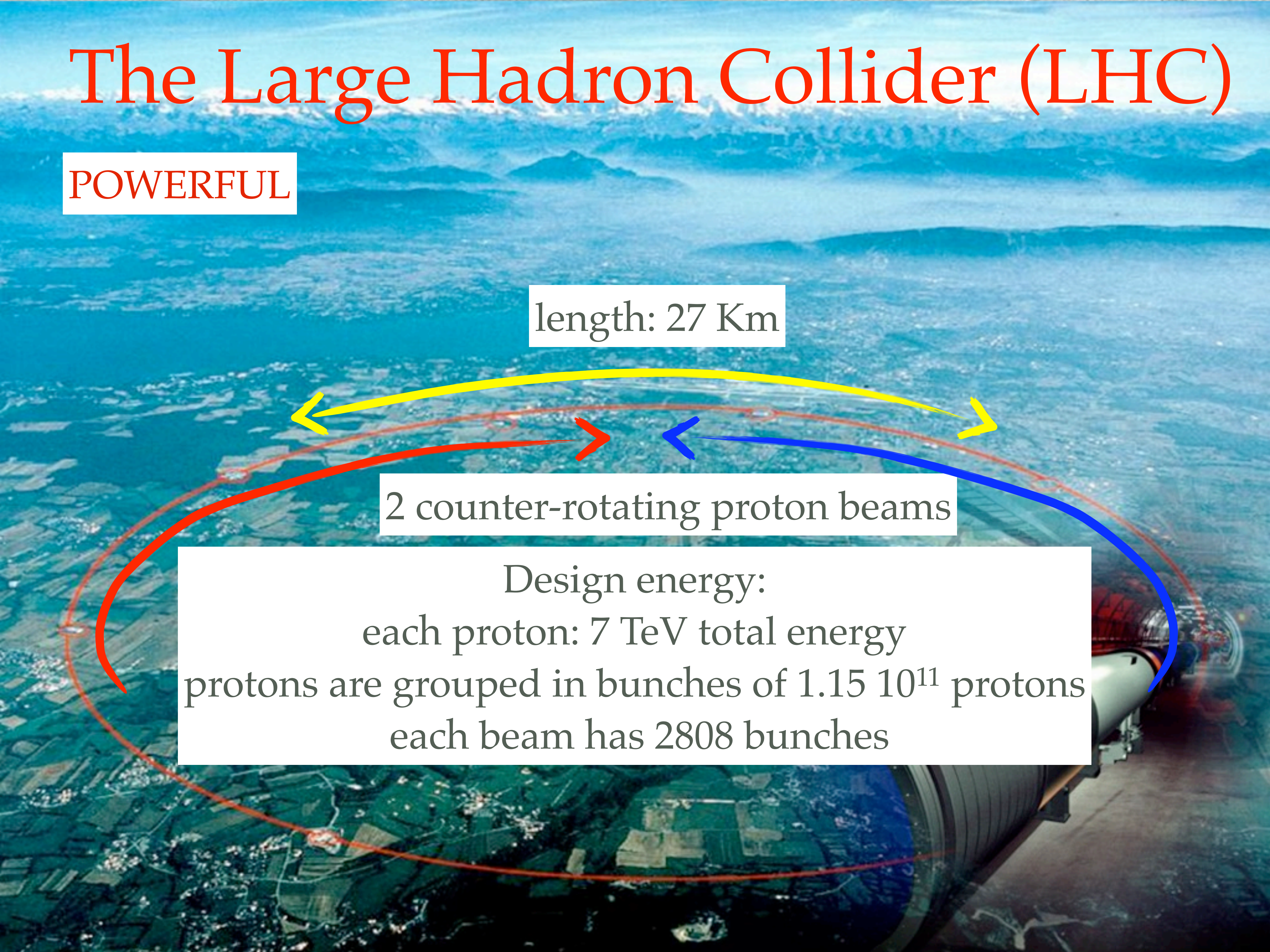


The Large Hadron Collider (LHC)

POWERFUL



length: 27 Km

2 counter-rotating proton beams

Design energy:
each proton: 7 TeV total energy
protons are grouped in bunches of 1.15 10^{11} protons
each beam has 2808 bunches

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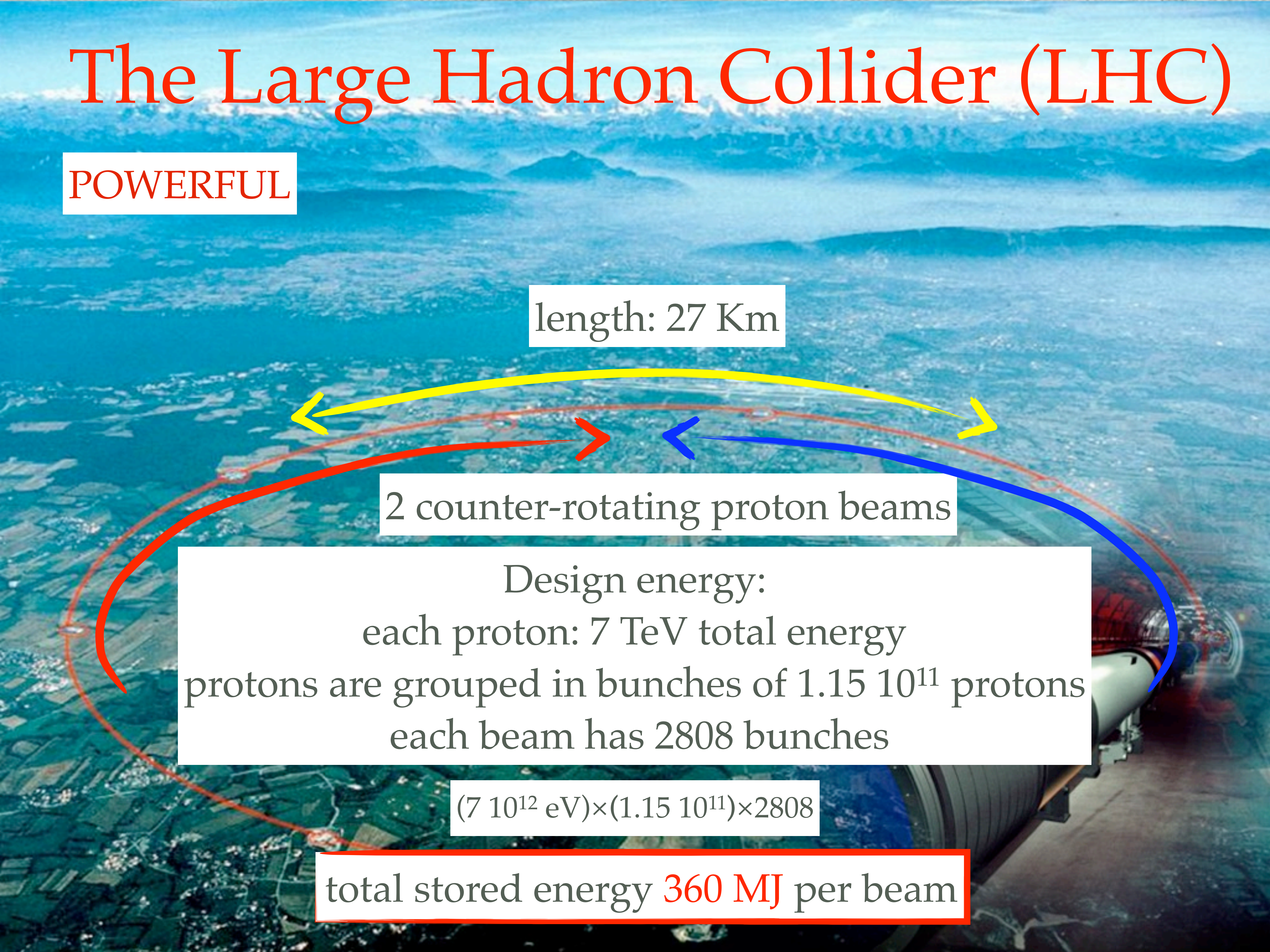

POWERFUL

length: 27 Km

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$(7\ 10^{12}\ \mathrm{eV})\times(1.15\ 10^{11})\times2808$

total stored energy 360 MJ per beam

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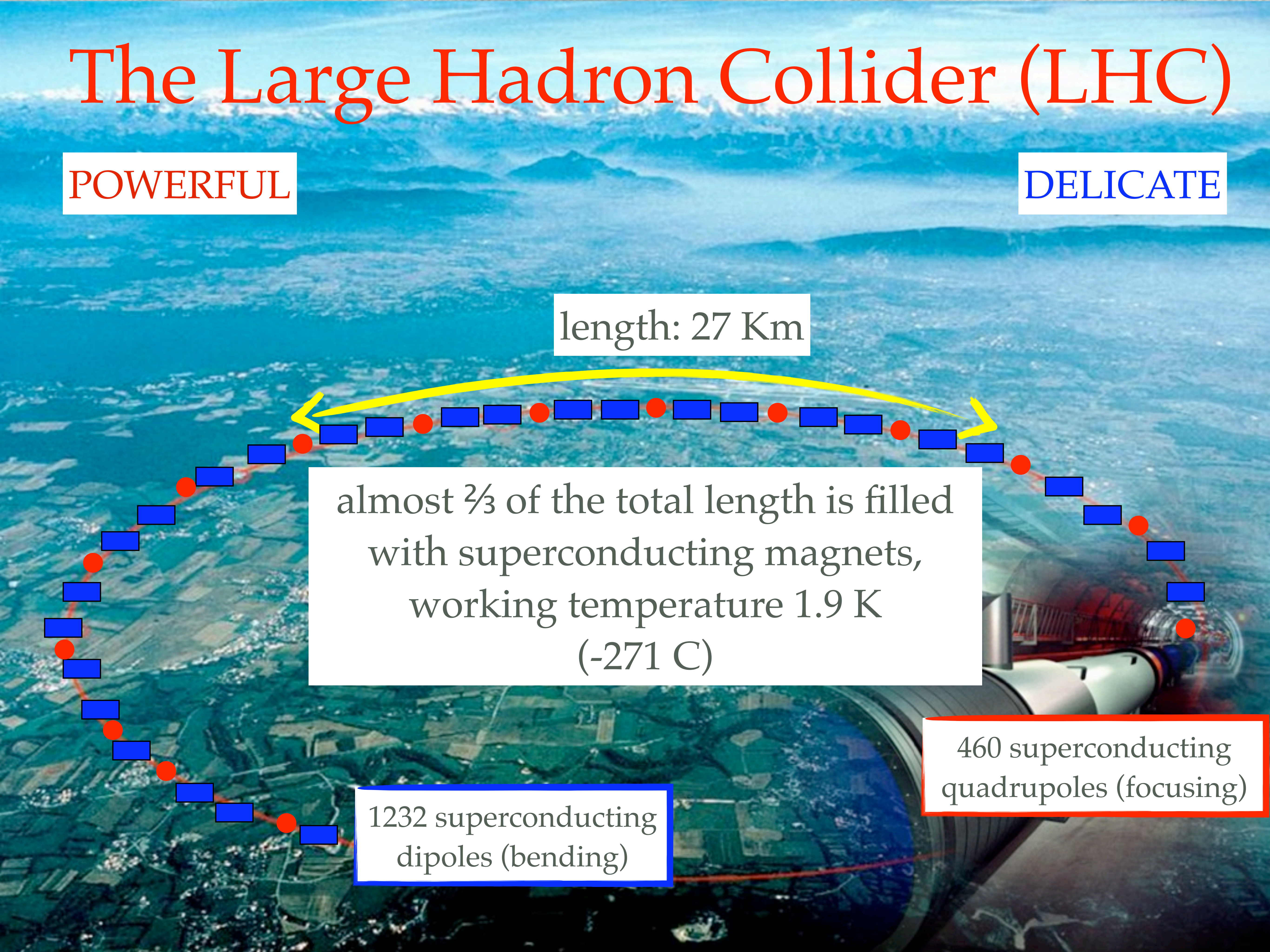

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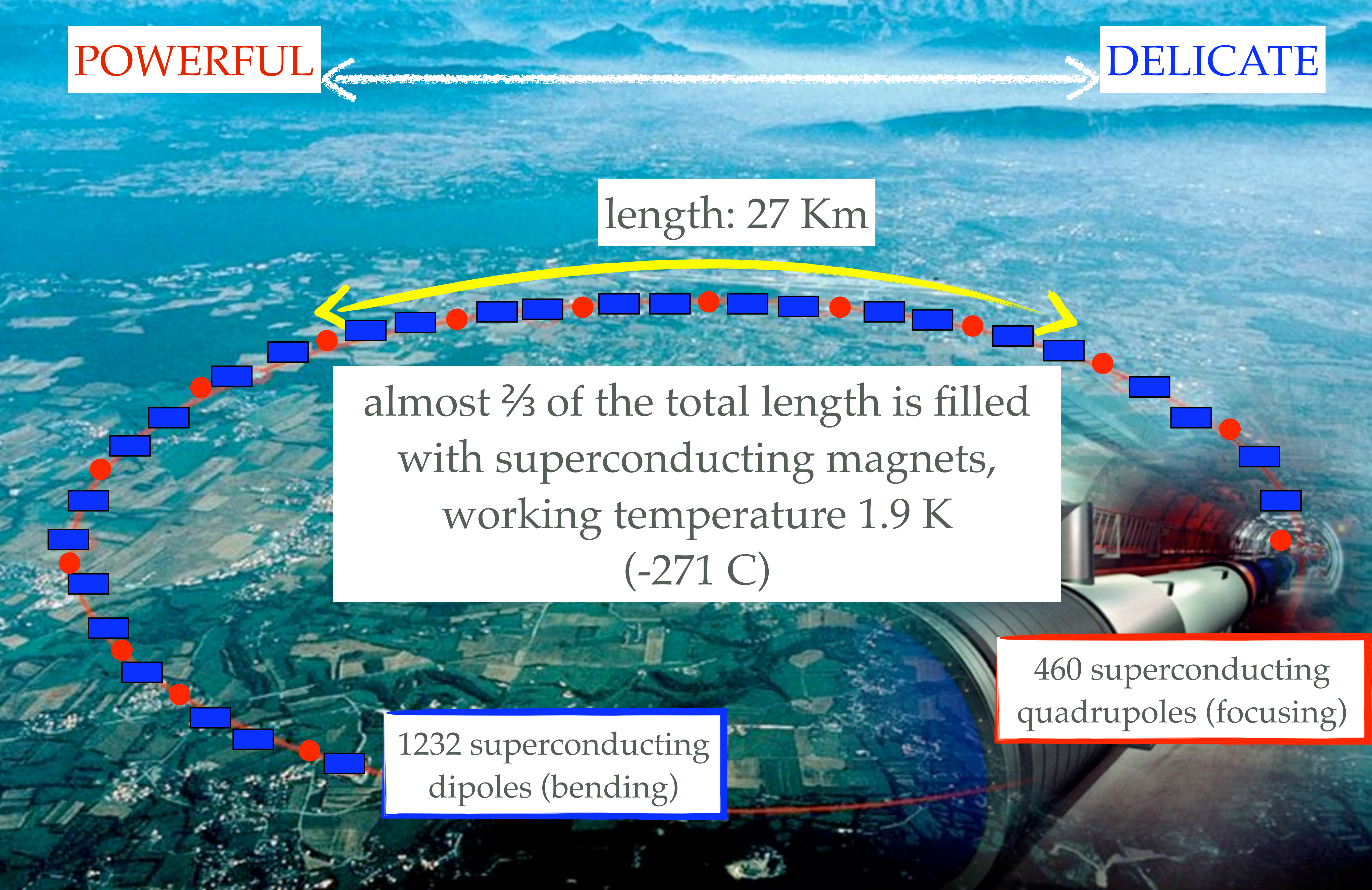

the Large Hadron Collider and its collimation system

POWERFUL ⟷ DELICATE

total energy

360 MJ per beam

working temperature

1.9 K

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Losses cannot be (totally) avoided

superconducting magnets are very sensible to energy releases

Design loss rate

(0.2h beam lifetime, 10 s)

$4.3\ 10^{11}$ p/s

=(480 KW per beam)

Quench limit

(energy release limit)

$7.8\ 10^{6}$ p/s/m

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Maximum local cleaning inefficiency

$$\eta = \frac{N_{abs}(dl)}{N_{Tot} \cdot dl} = 1.78\ 10^{-5}\ [1/m]$$

The challenge

Maximum local cleaning inefficiency $\eta = \frac{N_{abs}(dl)}{N_{Tot} \cdot dl}$ **= 1.78 10^{-5} [1/m]**

- if a "cleaning efficiency" performance of 10^{-5}/m cannot be achieved ➔ the circulating current must be proportionally scaled down (or the lifetime increased)

- but careful: the luminosity L of a machine is proportional to the total stored energy ➔ the collimation system limitations directly affect the machine performances! A performing collimation system is vital for the physics program of LHC.

The challenge

Maximum local cleaning inefficiency $\eta = \frac{N_{abs}(dl)}{N_{Tot} \cdot dl}$ **= 1.78 10^{-5} [1/m]**

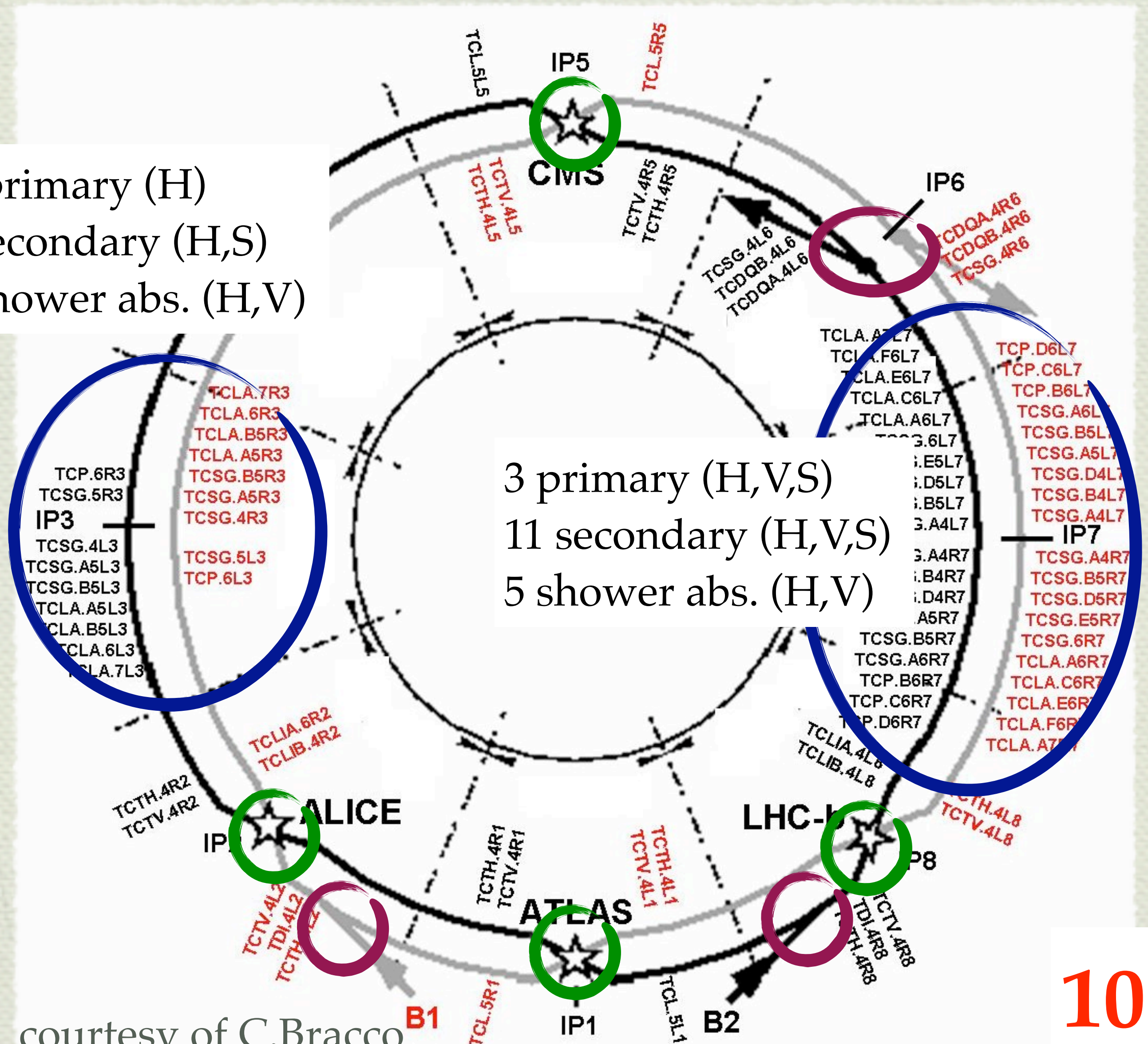
- if a "cleaning efficiency" performance of 10^{-5}/m cannot be achieved ➔ the circulating current must be proportionally scaled down (or the lifetime increased)
- but careful: the luminosity L of a machine is proportional to the total stored e … y affect the machin … s vital for the physics …

A sophisticated collimation system is required for a safe operation of the LHC.

phase 1: the most sophisticated collimation system ever…

phased approach ➔ divide goals and difficulties of LHC in time.

PHASE 1: Priority to robustness and flexibility (CFC).



1 primary (H)
4 secondary (H,S)
4 shower abs. (H,V)

3 primary (H,V,S)
11 secondary (H,V,S)
5 shower abs. (H,V)

courtesy of C.Bracco

Two warm cleaning insertions
IR3: Momentum cleaning
IR7: Betatron cleaning

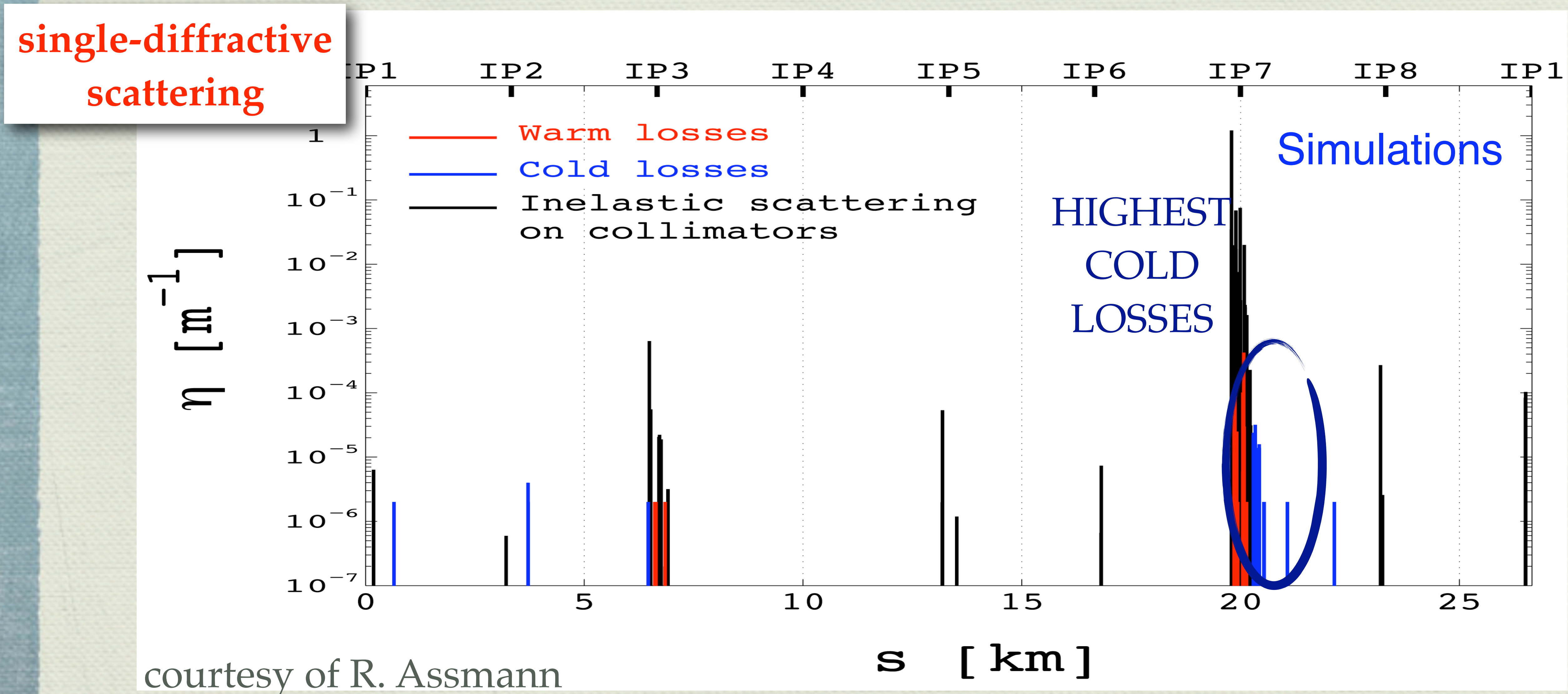
Local cleaning at triplets
8 tertiary (2 per IP)
Passive absorbers for warm magnets
Physics debris absorbers

Transfer lines (13 collimators)
Injection and dump protection (10)

108 collimators and absorbers!

… but still limited!

basic limitation of the collimation system: losses receiving a small kick but a non negligible $\Delta p/p$ escape the collimation insertion but are immediately lost at the first bending magnets



courtesy of R. Assmann

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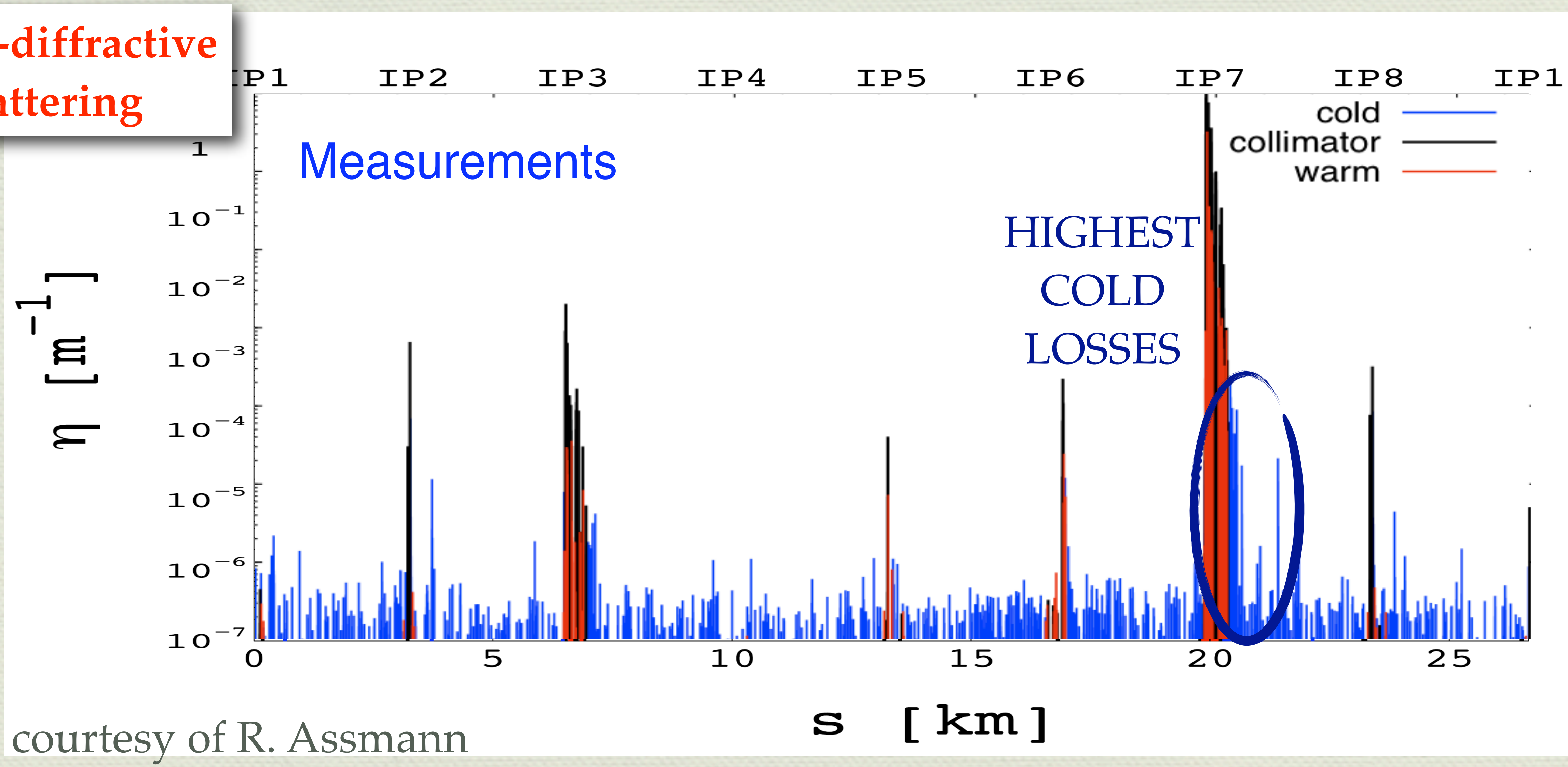
single-diffractive scattering



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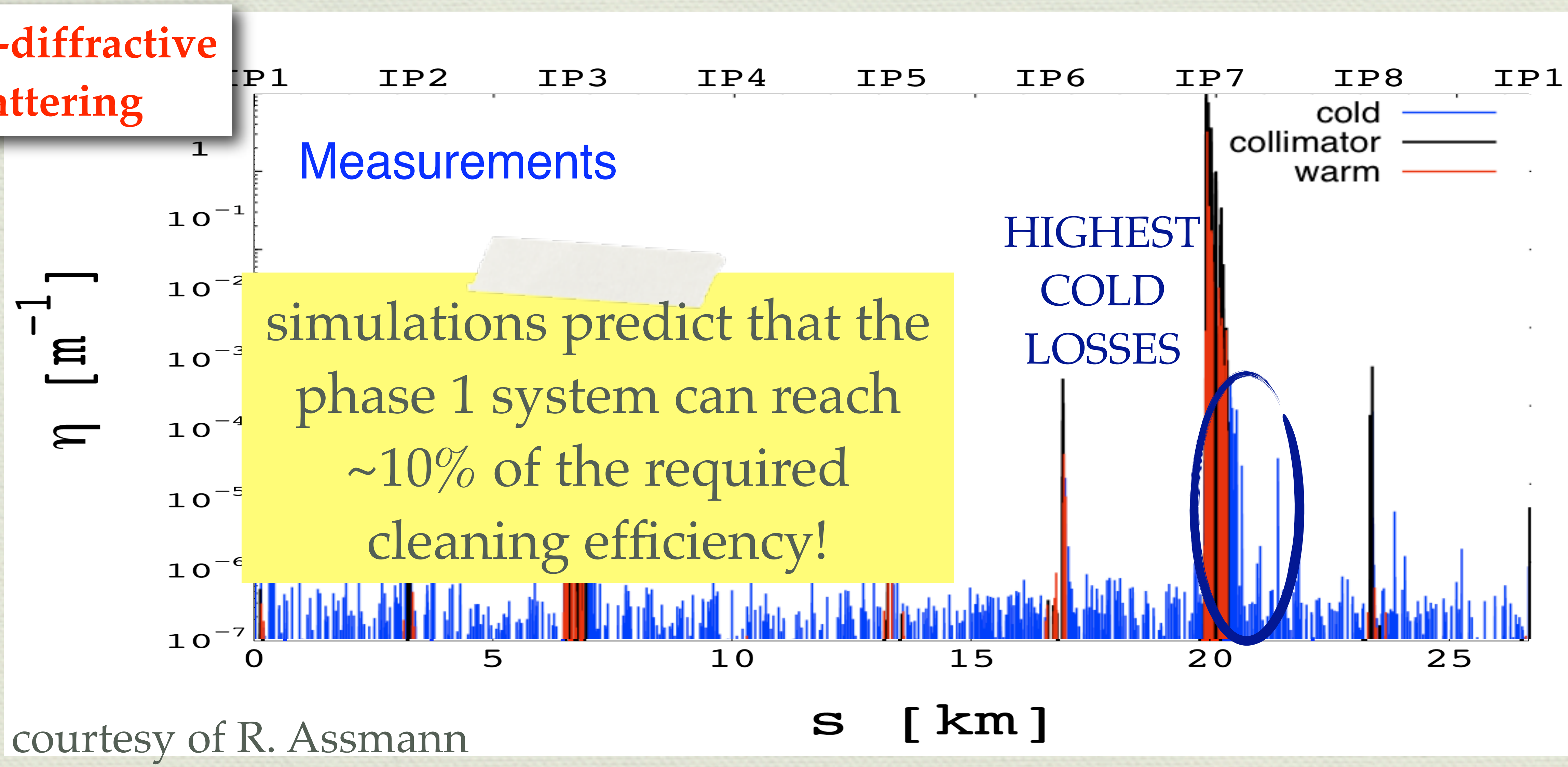


simulations predict that the phase 1 system can reach ~10% of the required cleaning efficiency!

courtesy of R. Assmann

the LHC collimation system: a phased approach

1. PHASE 1: Priority to robustness and flexibility (CFC).

simulations predict that the phase 1 system can reach ~10% of the required cleaning efficiency!

2. PHASE 2 will allow to reach the nominal luminosity. Insertion of metallic collimators+ cryogenic collimators.

simulations predict 100% of the required performances

3. UPGRADE: in attempt to go beyond the nominal LHC parameters, there is room for advanced collimation solutions like **crystals**.

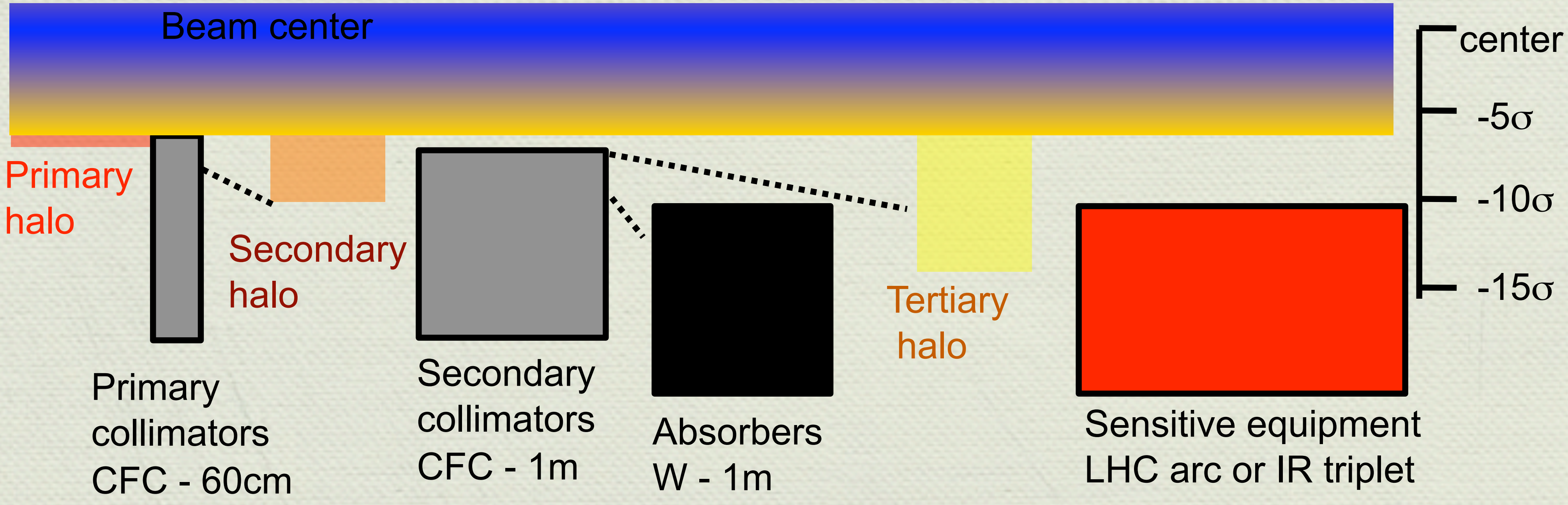
aiming at a factor 10 improvement

PHASE 1

How could a Crystal help?

Present layout of the LHC collimation system: multi-stage cleaning.

The primary collimators intercepts the primary beam halo - the halo is "sprayed" and intercepted downstream.

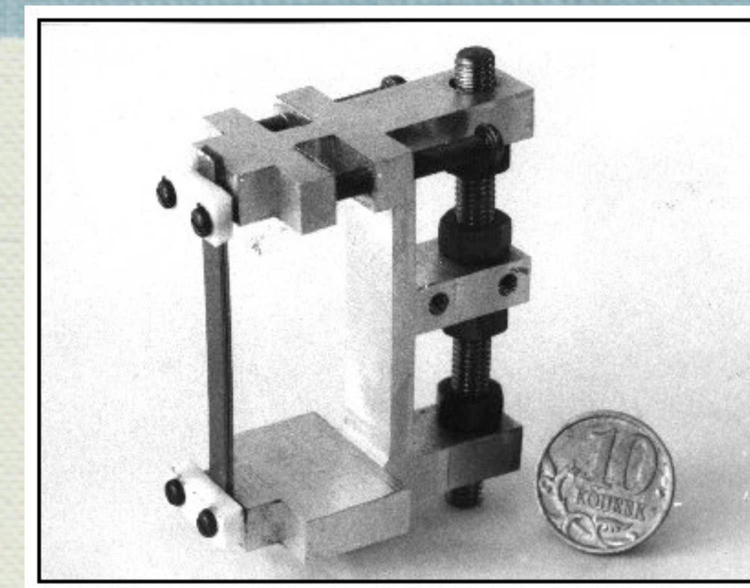


amorphous scatterer

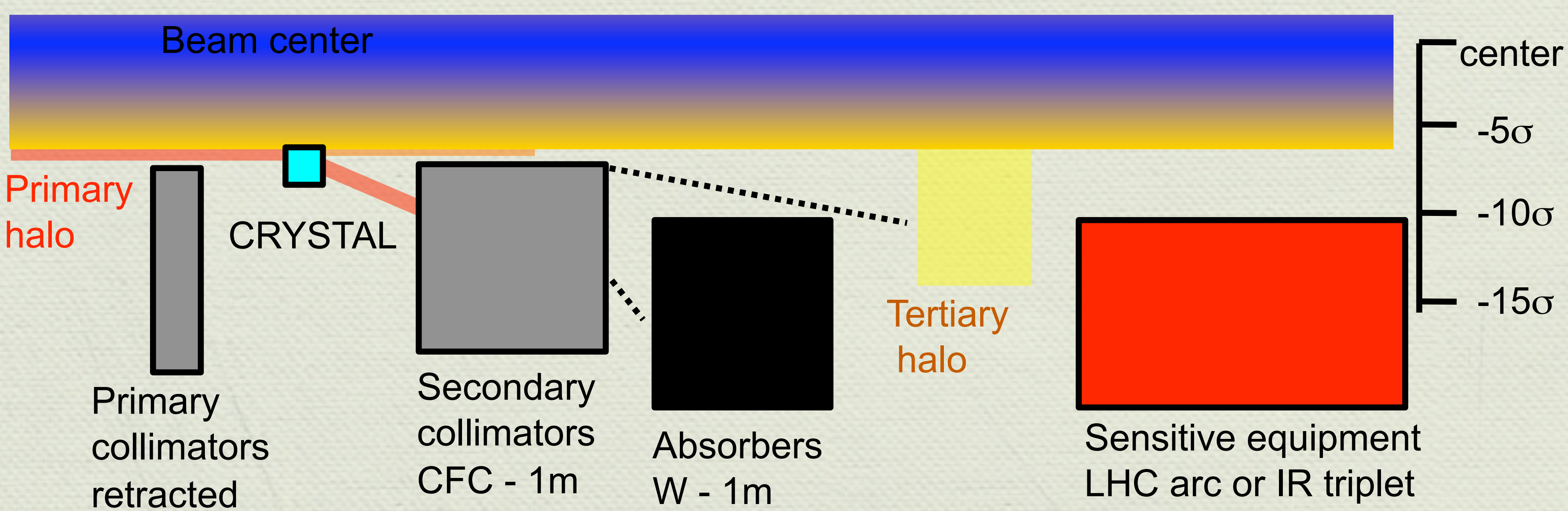
How could a Crystal help?

the idea: extracting the halo

The idea: to use mechanically bent crystals (typically Si) as "**smart scatterers**" in replacement of primary amorphous collimators, to minimize the escaping particles. Primary collimator would be slightly retracted.

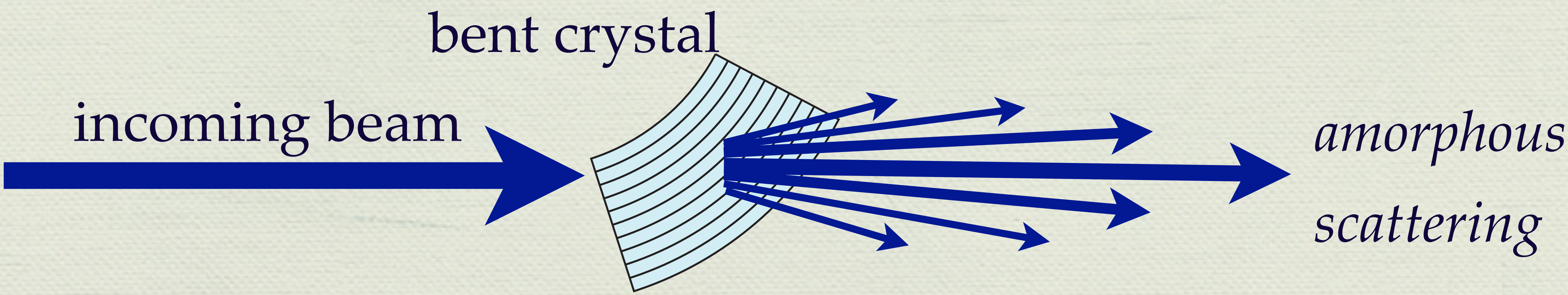


courtesy of W.Scandale



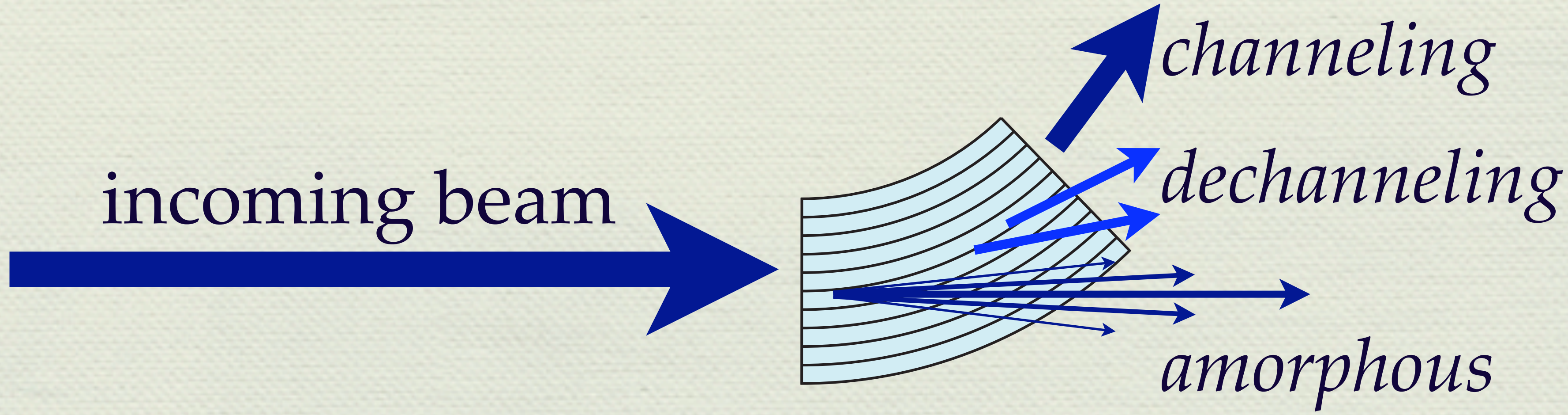
how does a crystal work?

it depends on the crystal-beam relative orientation!



Beam not aligned ➔ Amorphous behavior:

As the standard collimators
~ Gaussian distribution of angular kicks
due to the overlap of different effects
(MCS, ionization, excitation, nuclear interactions…)



Channeling

- efficiency: 50%
- kick:100-500 urad
- acceptance: 2-20 urad

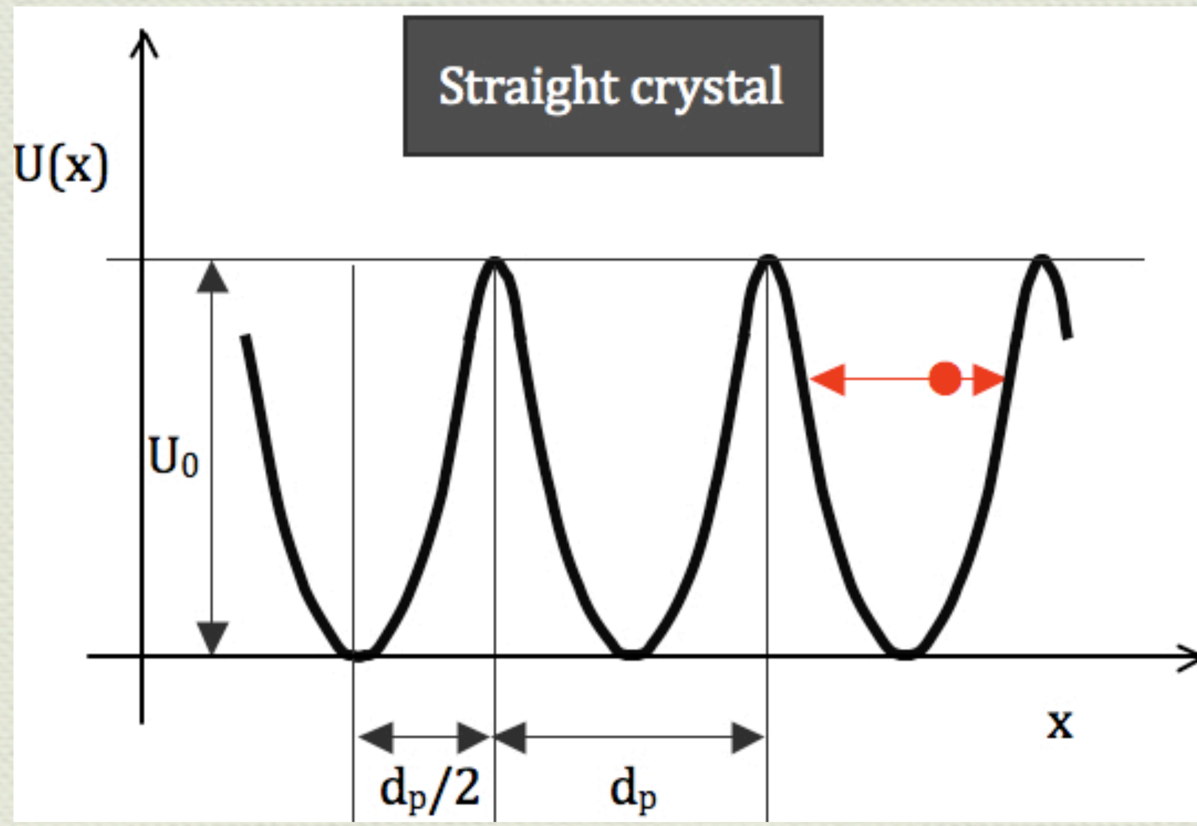
(depends on energy)

transerve particle energy

$$\frac{pv}{2}\theta^2 + U(x) < U_0$$

planar potential

Max. planar potential

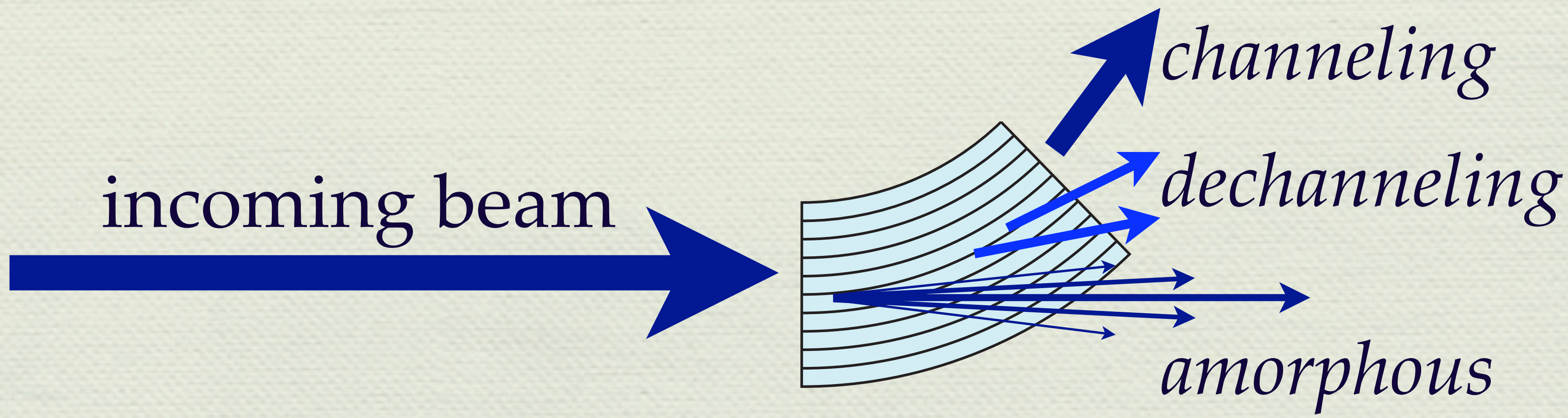


if the particle transverse energy is lower than the maximum planar potential, the particle is trapped and follows the crystal planes

for the bent crystal, the effective potential is slightly reduced by a centrifugal term, and so the channeling acceptance

Channeling mode

Channeling mode



Channeling
- efficiency: 50%
- kick:100-500 urad
- acceptance: 2-20 urad (depends on energy)

$$\frac{pv}{2}\theta^2 + U(x) < U_0$$

transerve particle energy

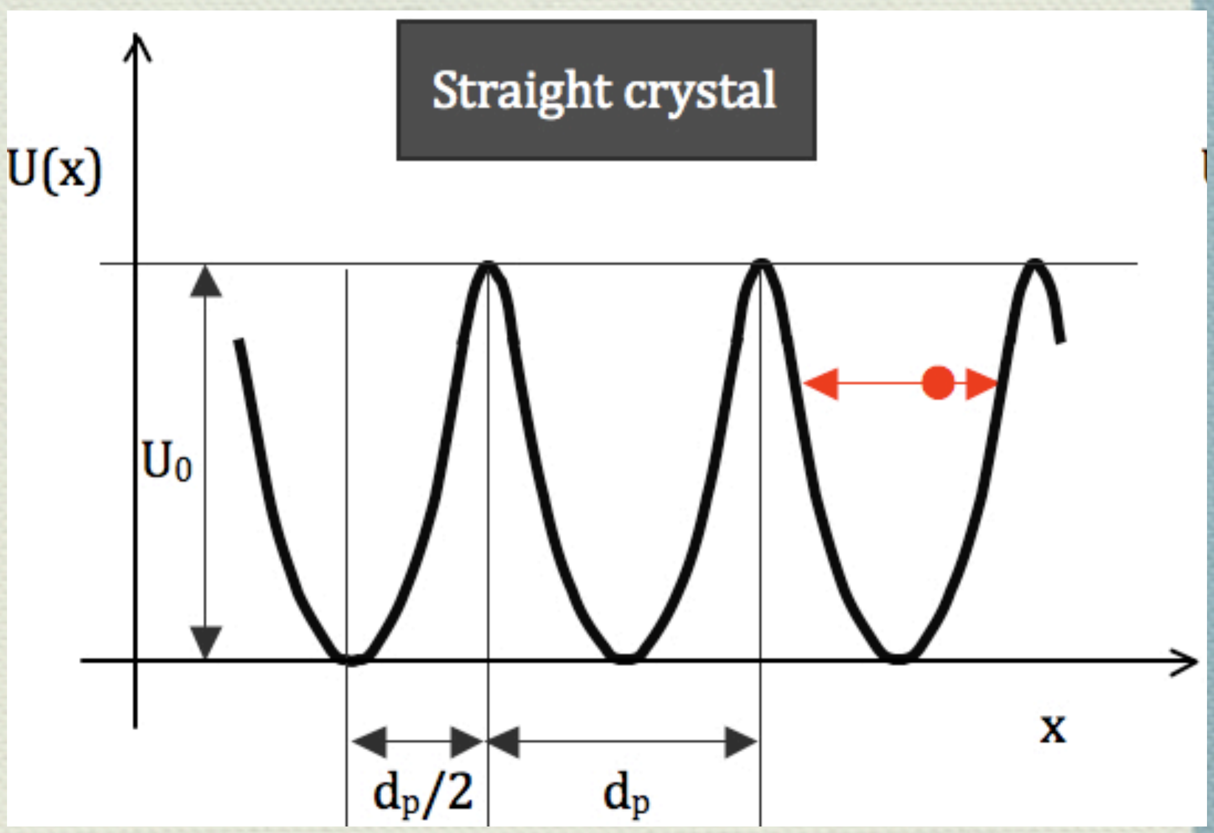
pv=7 TeV

planar potential

U(0)=0

Max. planar potential

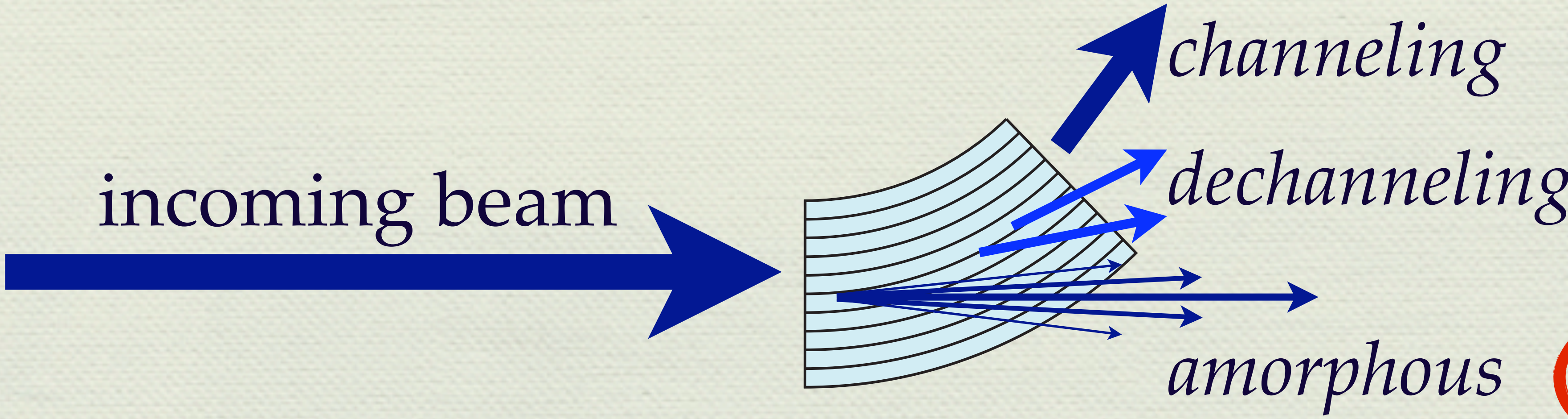
U_0=30 eV



maximum angle w.r.t. crystal planes

$$\theta_{C0} = \sqrt{\frac{2U_0}{pv}}$$ **= 2.9 10^{-6}rad**

about 2 10^{-6}rad in case of "LHC" bent crystal



Channeling
- efficiency: 50%
- kick:100-500 urad
- acceptance: 2-20 urad
(depends on energy)

is the impacting halo divergence within the acceptance?

a natural spread in angular distribution for particle grazing the crystal surface exists!

➔ extensive theoretical studies on the expected angular spread have been done

results for LHC: angular spread 0.25 μrad

channeling acceptance ~ 2 μrad

SAFE!

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Grazing function *g* and collimation angular acceptance

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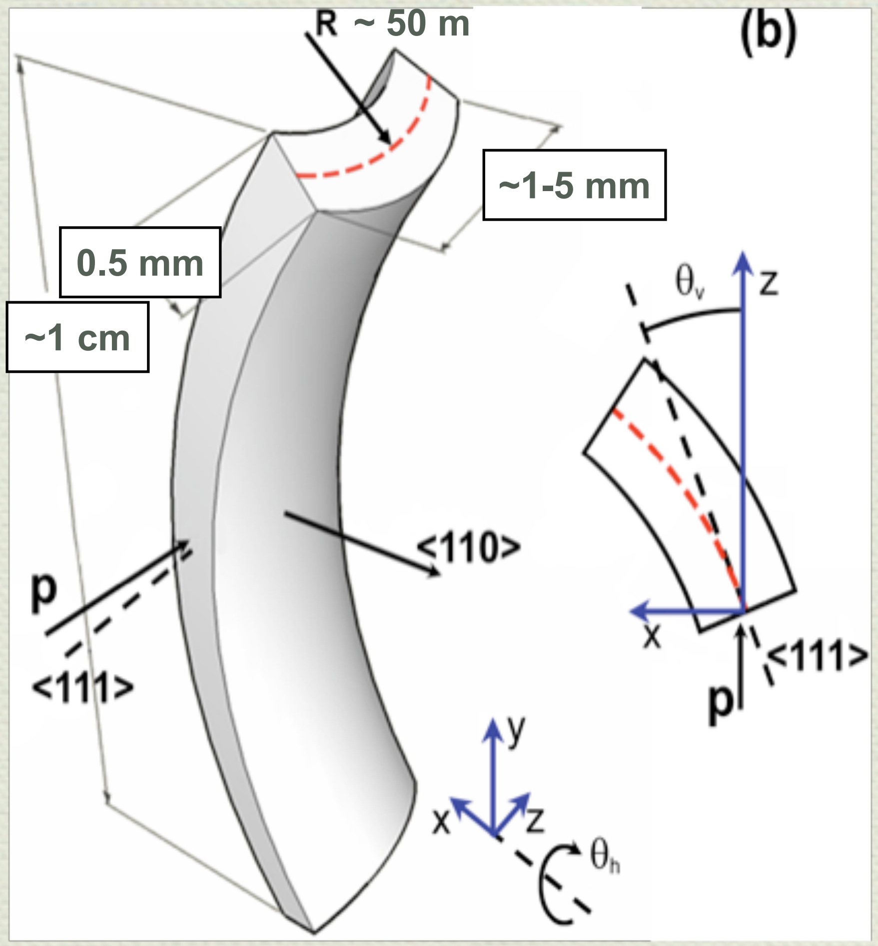
why a crystal? and not (for example) a magnetic field?

- Tiny but powerful object
- Most common crystals are made of Si and their longitudinal length is between 1-5 mm
- with the channeling effect, a crystal is capable of extracting multi Tev particles deviated of hundreds of urad in a very short length (mm)
- a crystal can select which particles to deviate!
    - if inserted at the center of the beam can be used for extraction
    - if touching only the halo particles ➔ use for collimation



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Bρ=3.335 p [GeV/c], for R~50 m ➔ B = 450T

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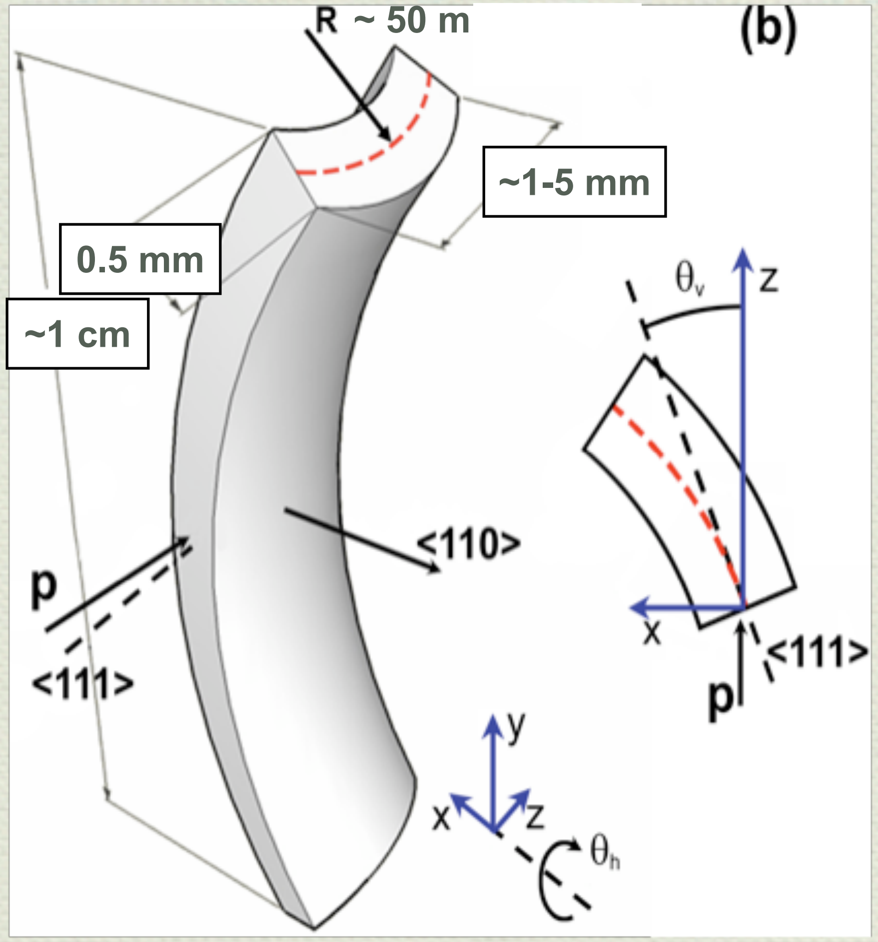
  - if touching only the halo particles ➔ use for collimation



very difficult to achieve with a standard magnet!

LHC simulations: Simulation inputs

- Si crystal strip crystal, installed in an empty slot in the collimation insertion
- 7 TeV standard collision optics
- Curvature radius of 50 m, different lengths, bending angles between 10 and 200 μrad
- Perfect alignment and perfect crystal
- Horizontal and vertical case studied separately 8 million particles for 500 turns.
- In the tracking software package, a detailed aperture model (both for SPS and LHC) is included. Local cleaning inefficiency evaluated for 27 Km, with a 10 cm bin.

	β [m]	α [-]	D [m]	1σ [μm]	$1\sigma'$ [μrad]
x direction	137.62	1.94	0.59	262	3.7
y direction	90.65	-1.25	0.002	213	2.9

Main outcome: Beam Loss Maps

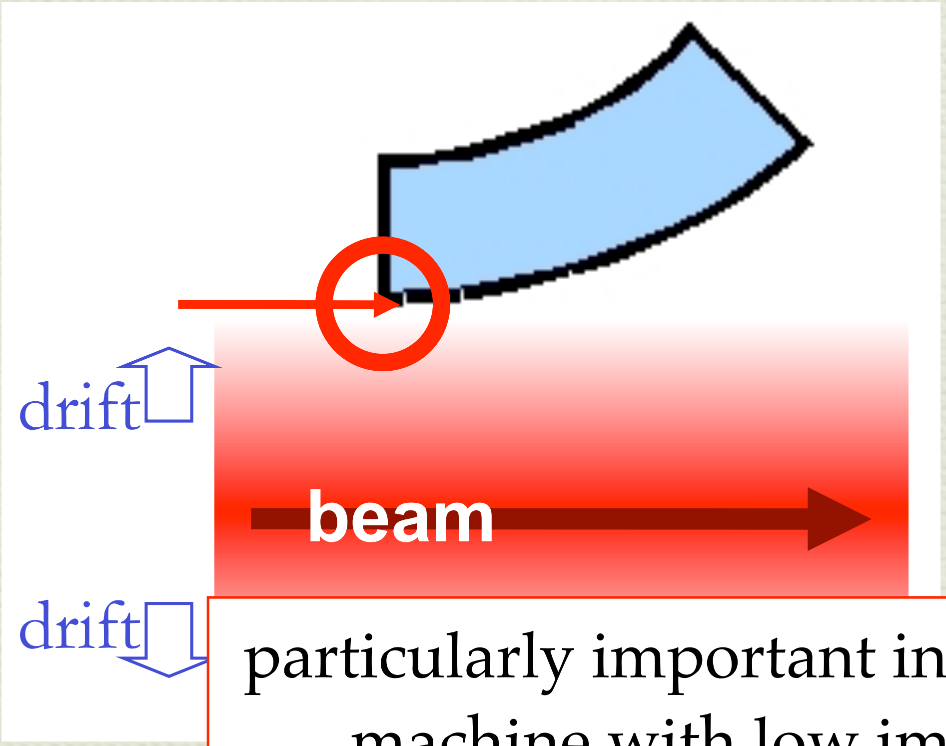
local collimation cleaning inefficiency η_{loc} vs longitudinal coordinate s

Simulation tools: crystal code Sixtrack

The “state of the art” tracking code SixTrack (currently used at CERN for collimation studies) is a full 6D tracking code, which treats the interaction for amorphus collimators.

For the first time, a Montecarlo routine describing the crystal was coupled to a massive parallel simulation code for fine evaluation of far away losses

- code adapted (variables, change of coordinates, output..)
- implementation of edge effects in the code (amorphous layer and miscut angle) particularly important in a circular machine

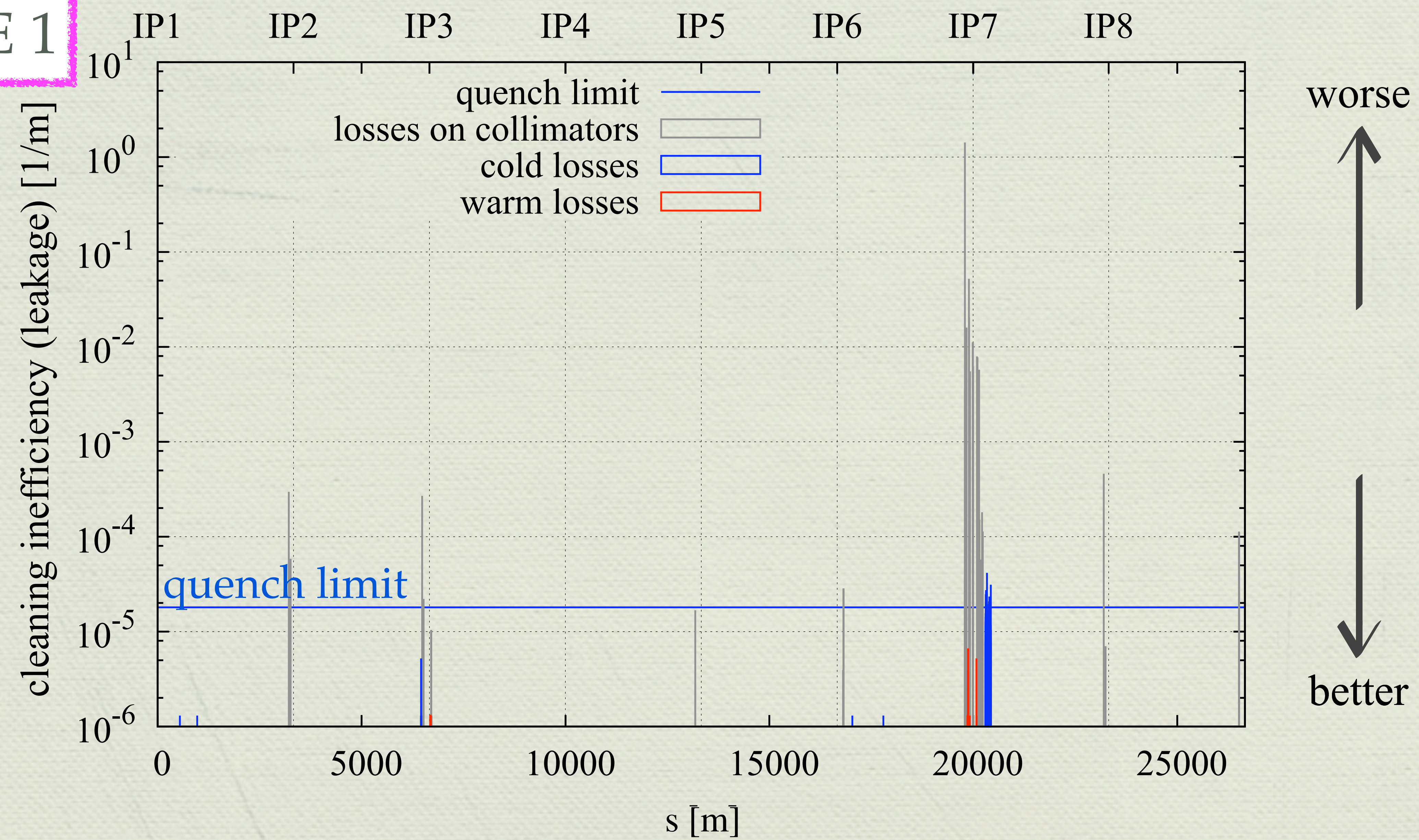


particularly important in circular machine with low impact parameters!

LHC loss maps - horizontal case

loss maps in IR7 and immediately downstream

PHASE 1



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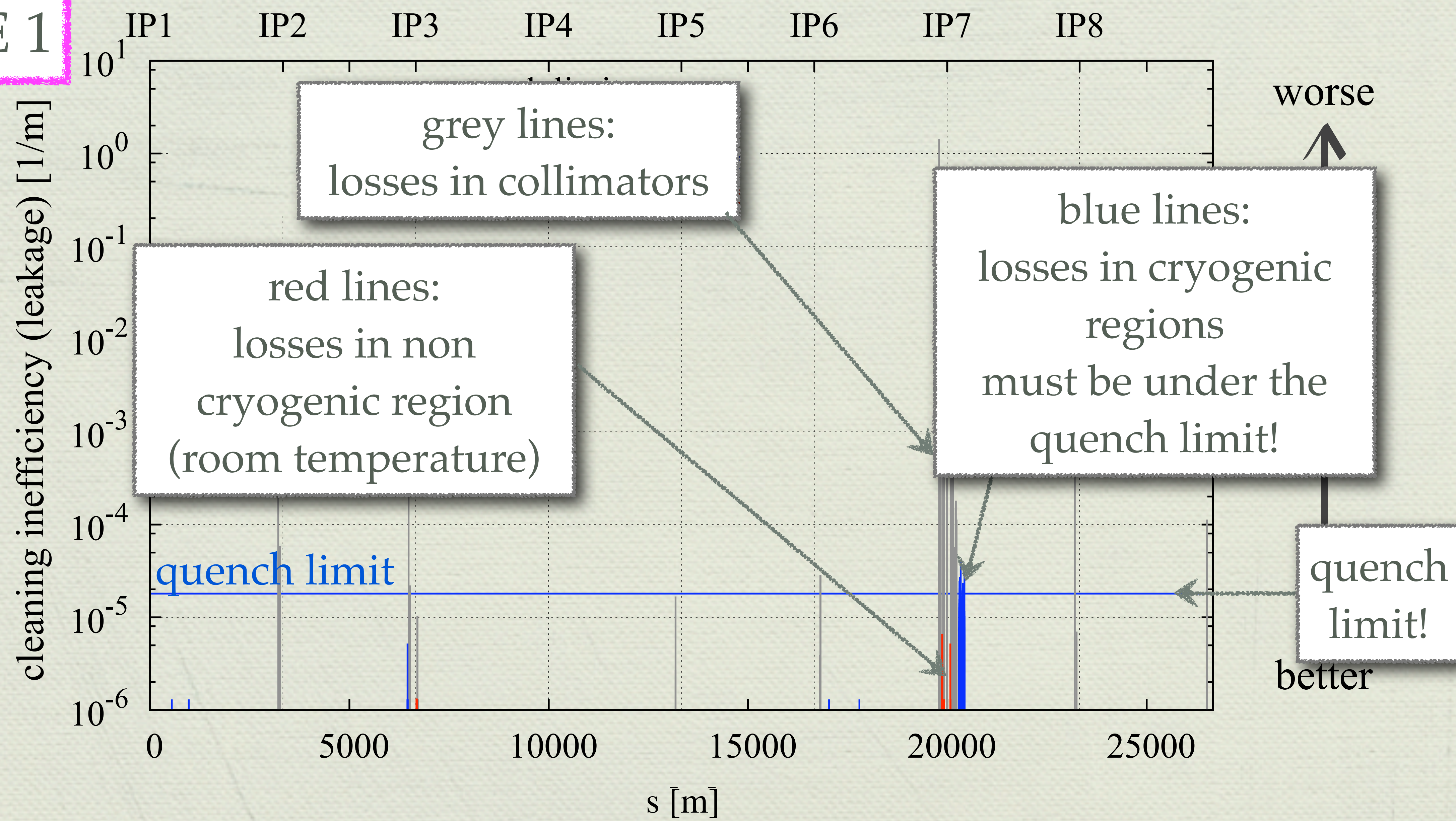

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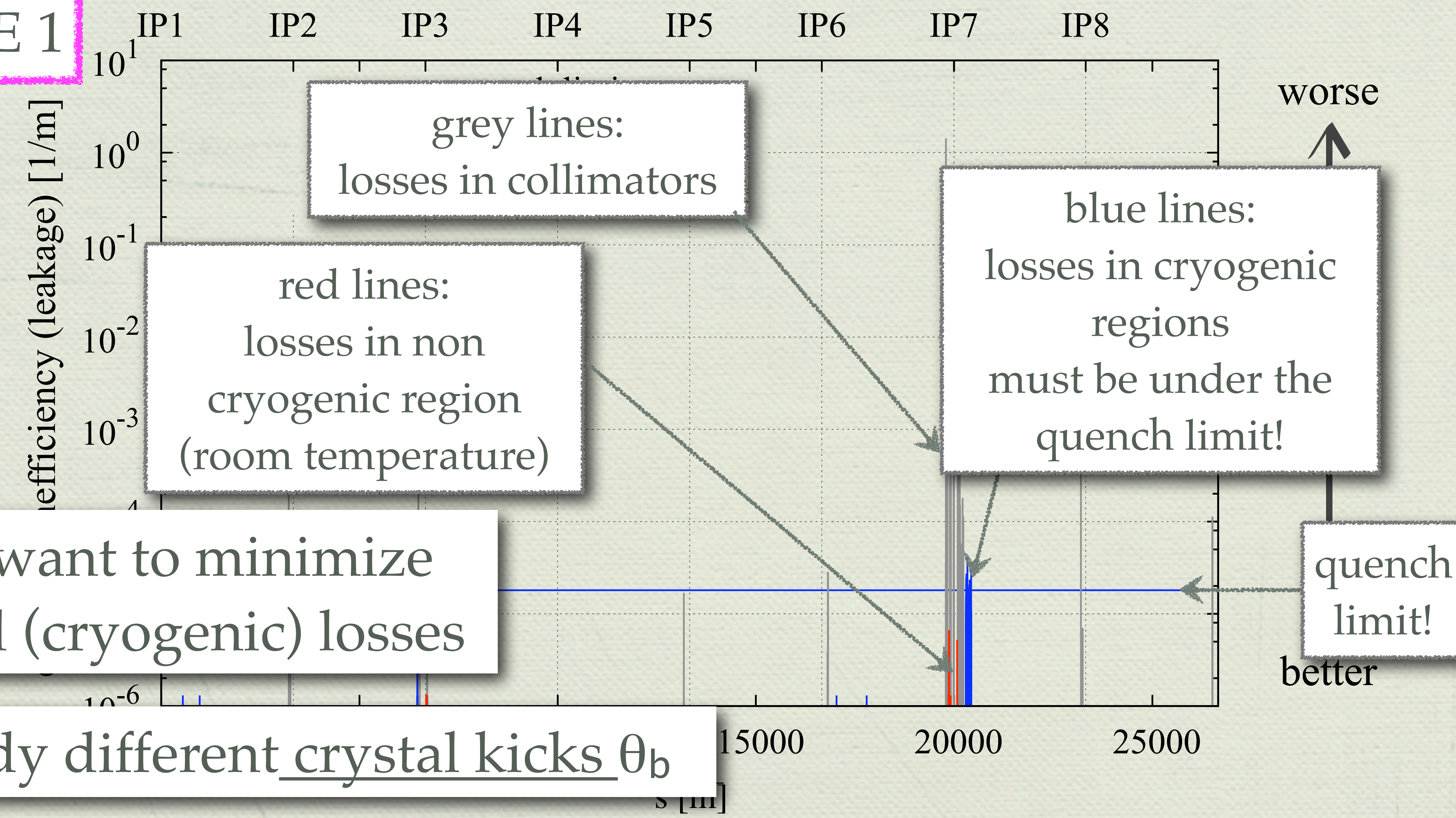

we want to minimize
cold (cryogenic) losses

study different crystal kicks θ_b

LHC loss maps - horizontal case

loss maps in IR7 and immediately downstream

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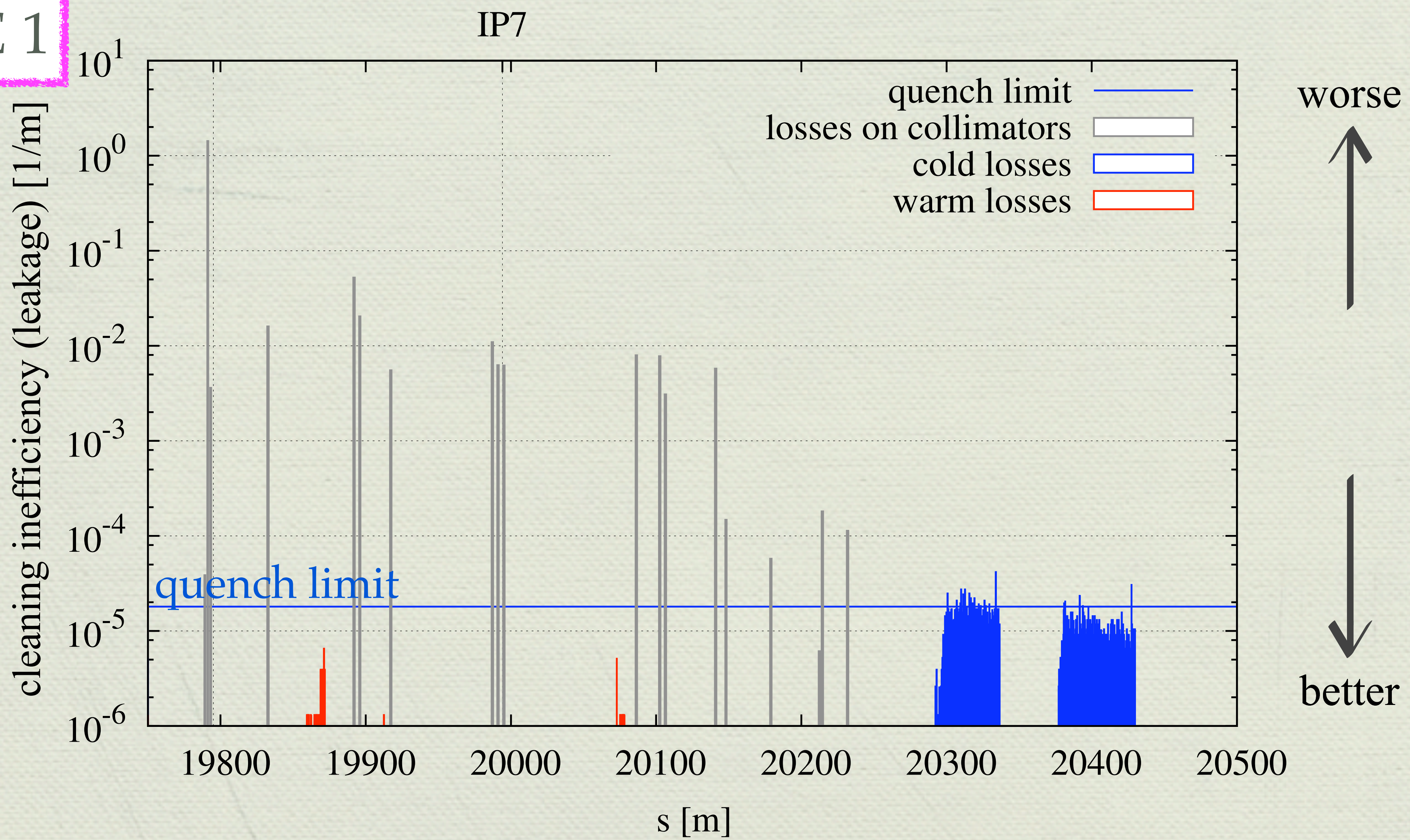
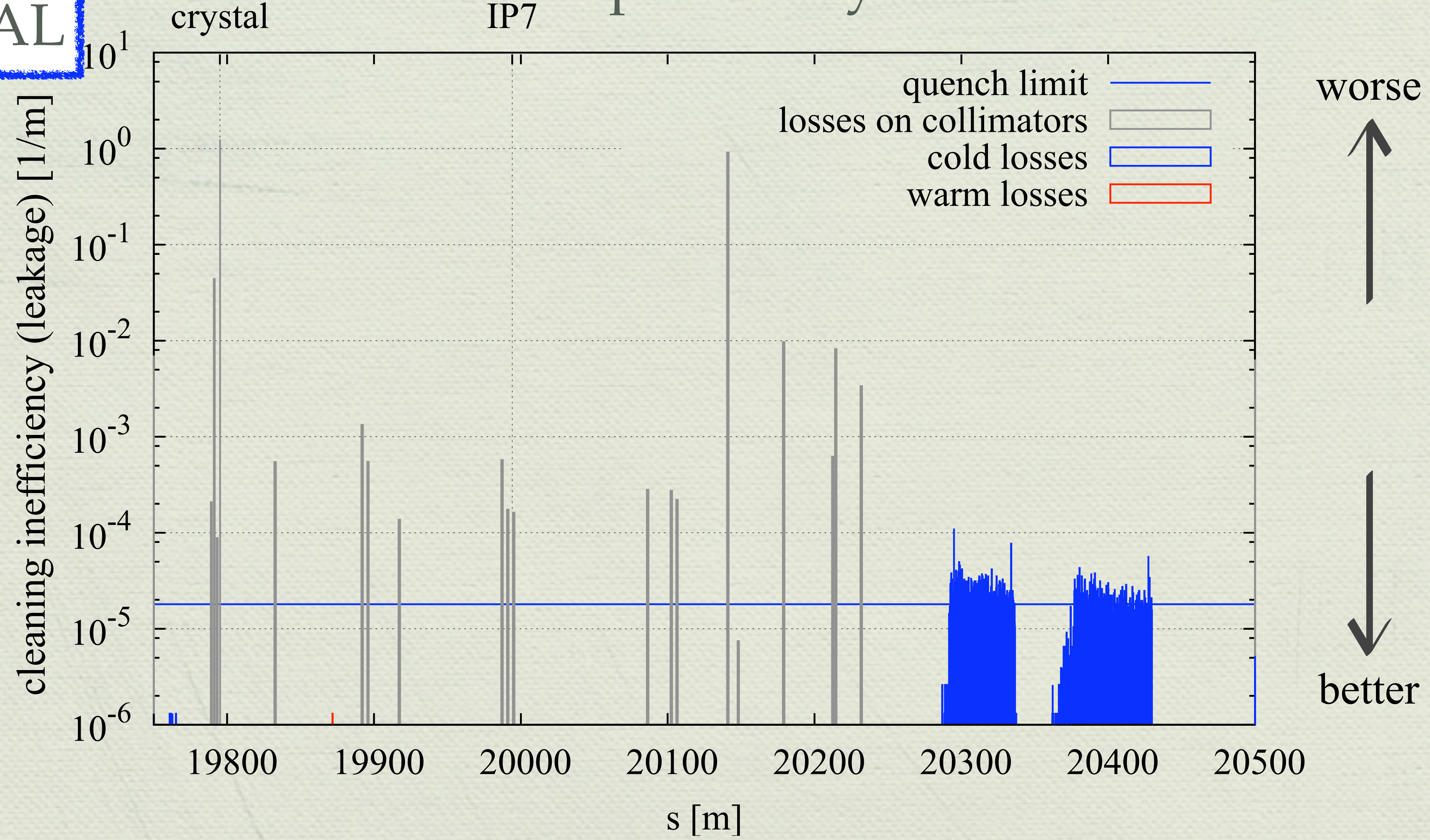


LHC loss maps - horizontal case

$\theta_b = 10\ \mu rad$

low channeling angle, result similar to phase 1 system

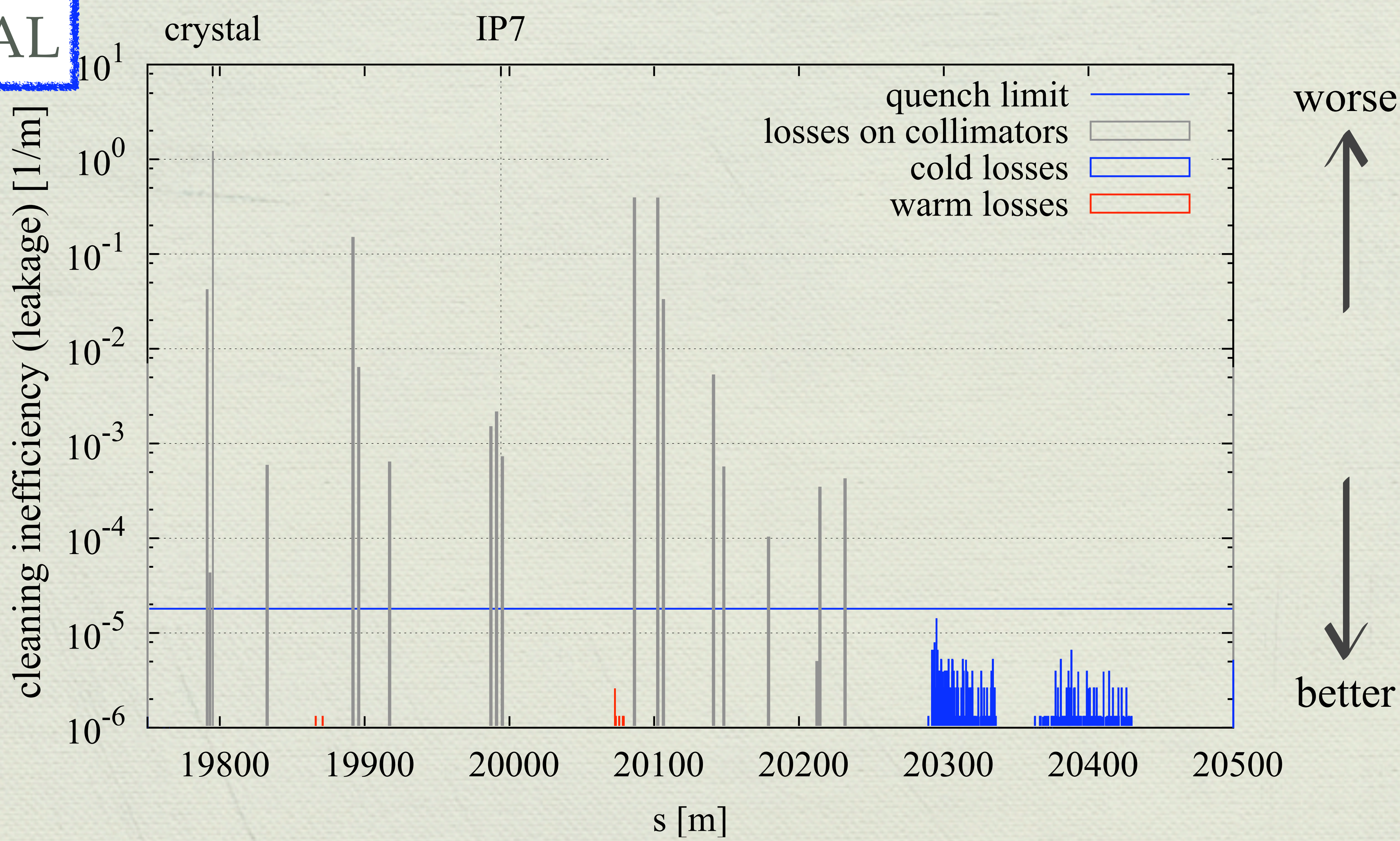
CRYSTAL



LHC loss maps - horizontal case

$\theta_b = 20\ \mu rad$

CRYSTAL

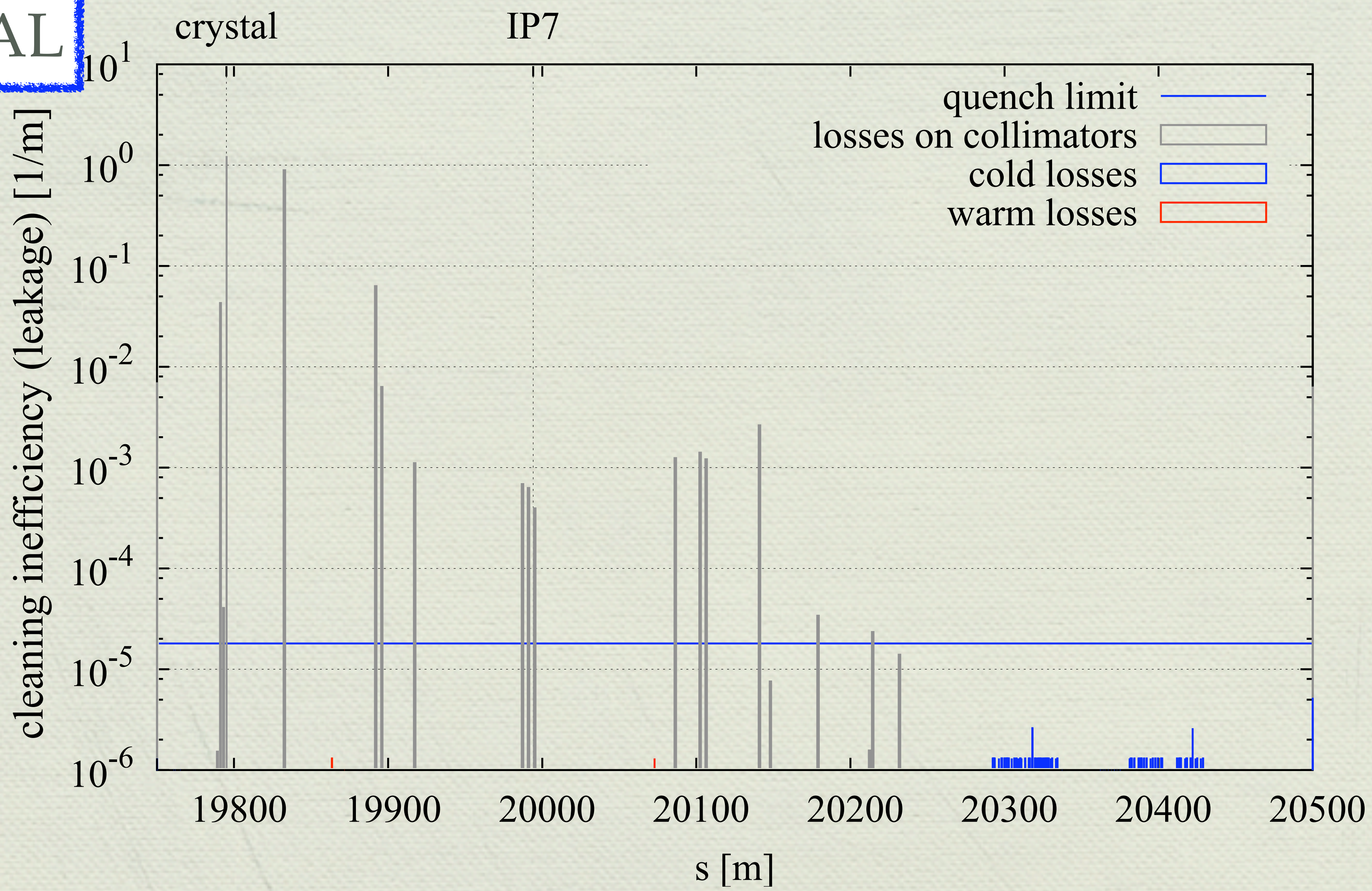


LHC loss maps - horizontal case

$\theta_b = 40\ \mu rad$

reach a minimum in losses

CRYSTAL



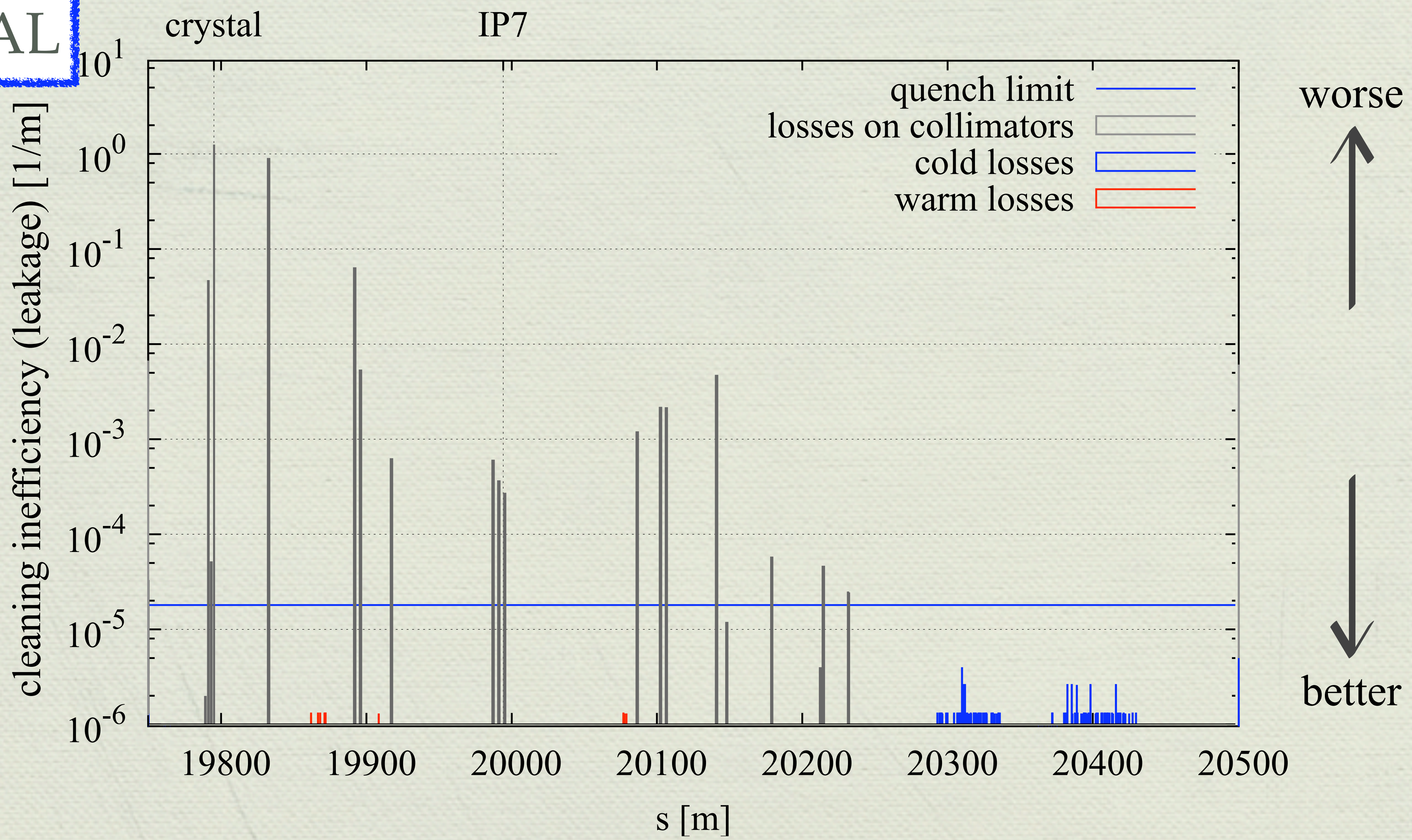
worse

better

LHC loss maps - horizontal case

$\theta_b = 50\ \mu rad$

CRYSTAL

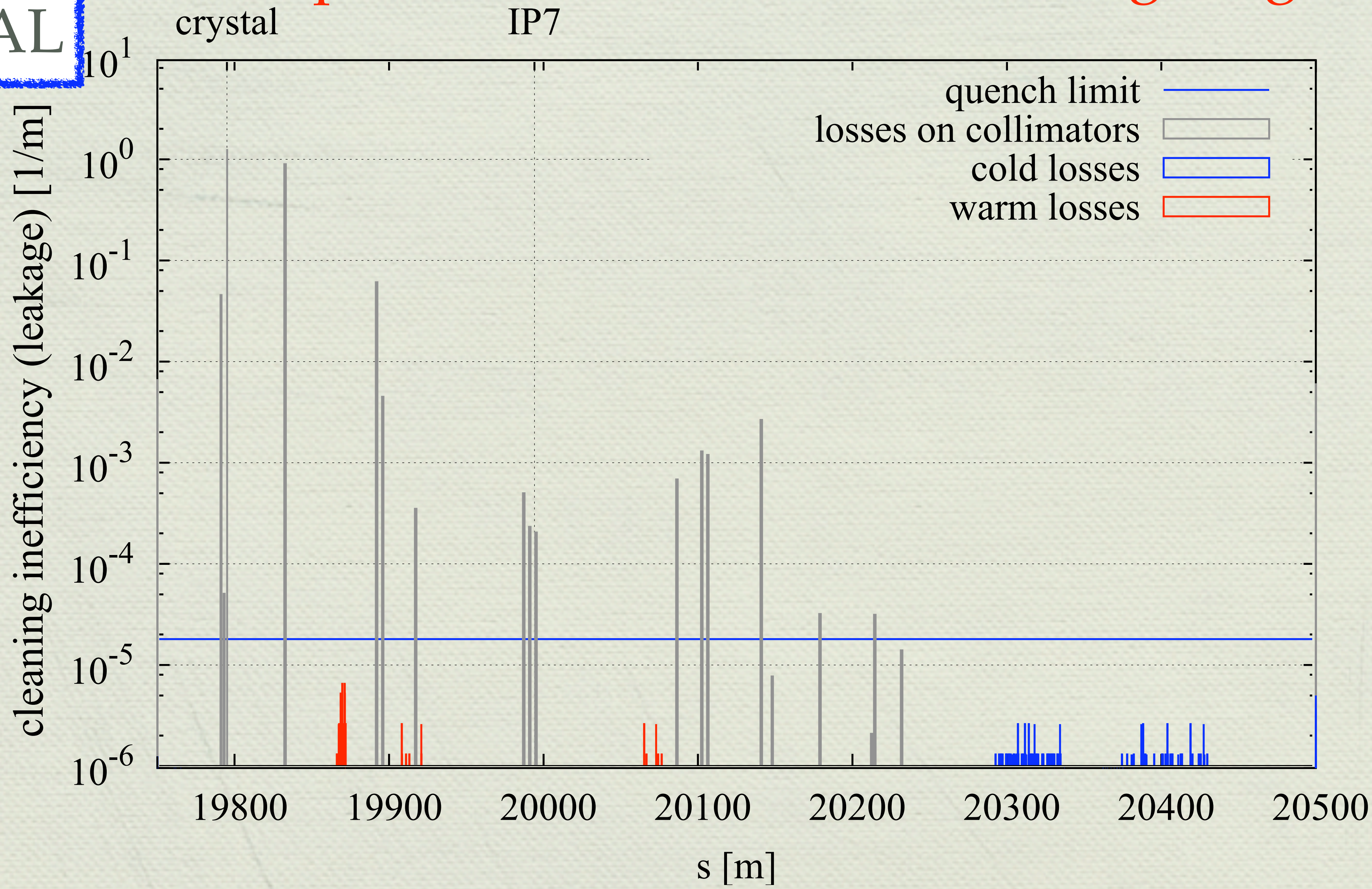


LHC loss maps - horizontal case

$\theta_b = 75\ \mu rad$

“warm” losses increasing! unwanted power deposition on normal conducting magnets

CRYSTAL



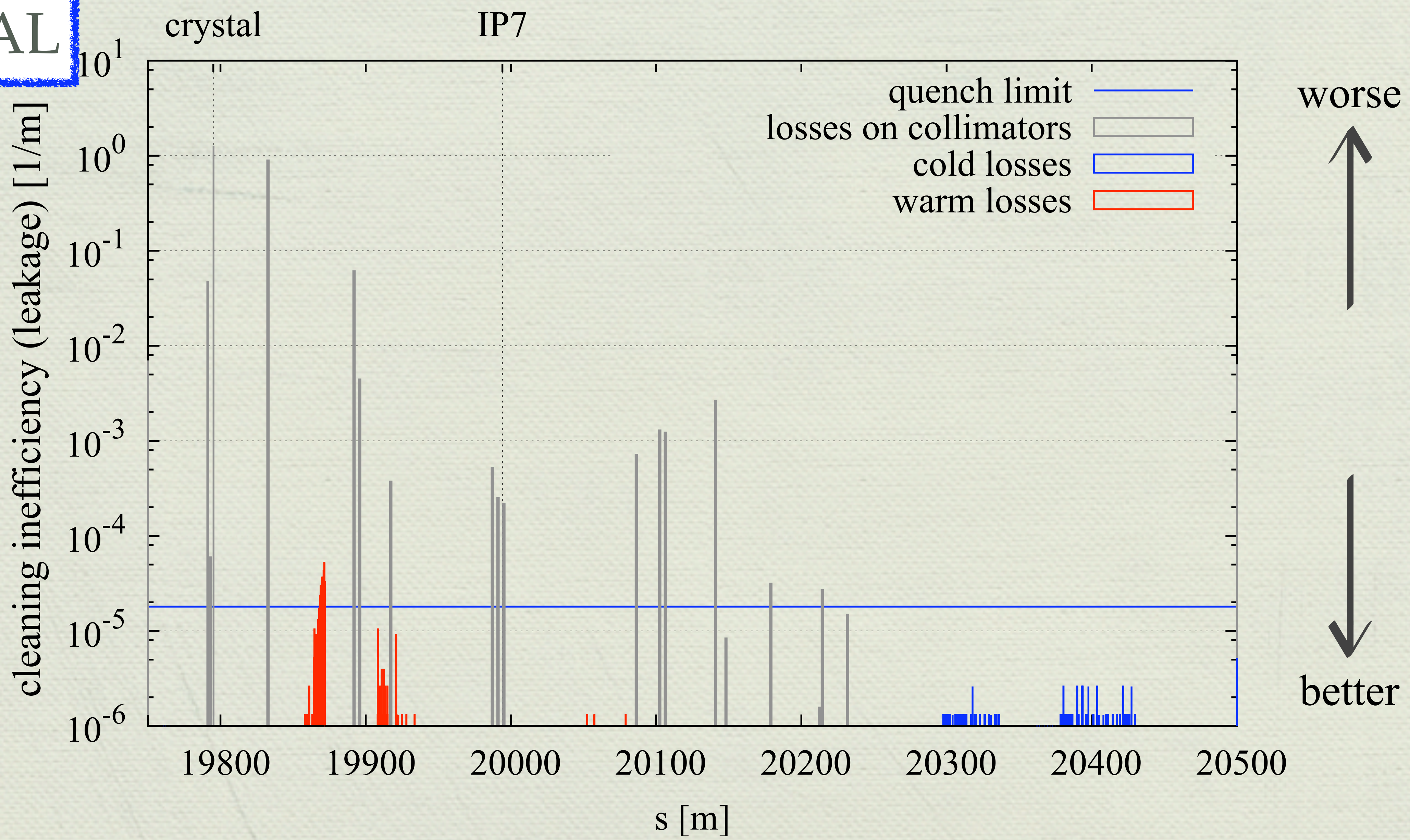
worse

better

LHC loss maps - horizontal case

θ_b =100 μrad

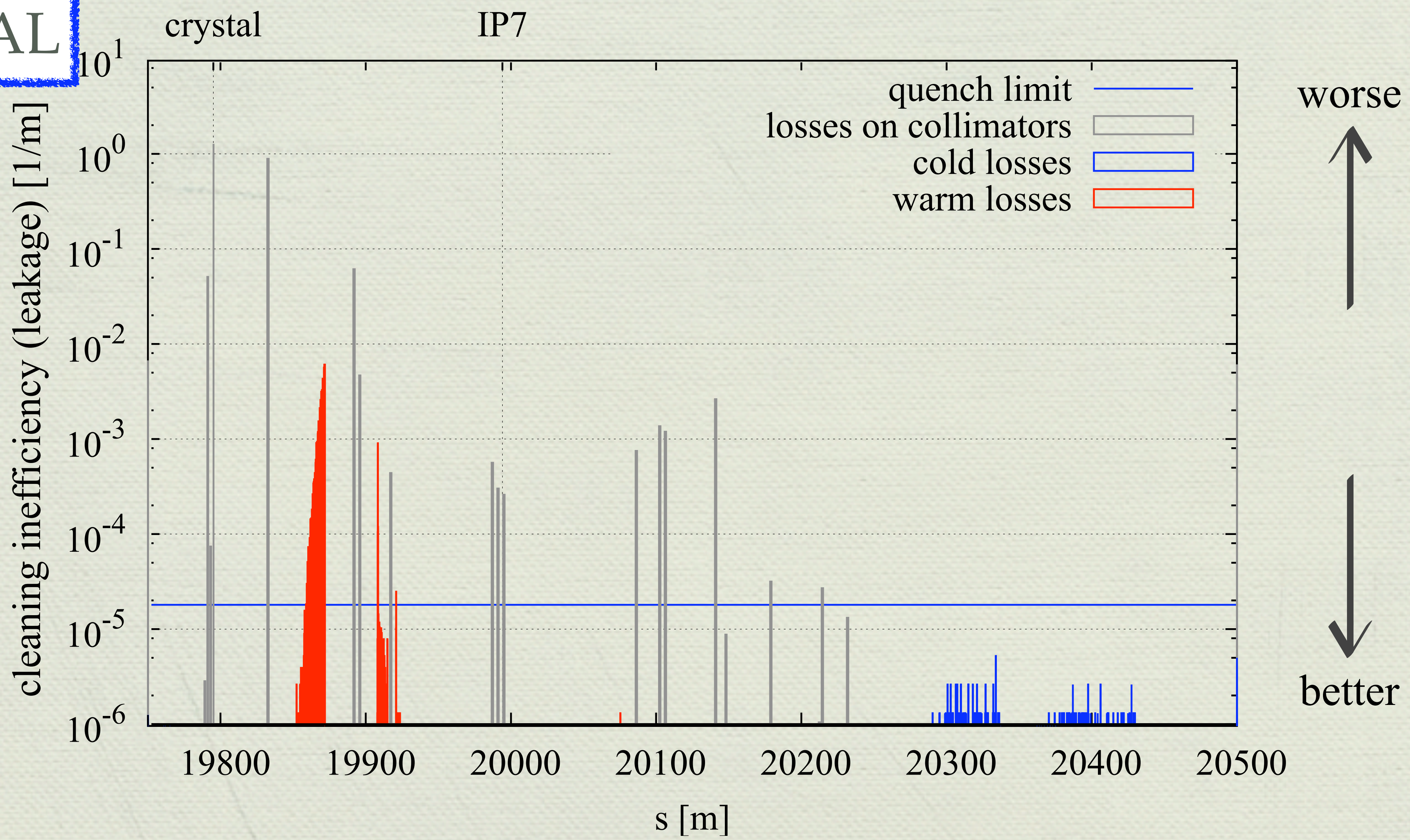
CRYSTAL



LHC loss maps - horizontal case

$\theta_b = 150\ \mu rad$

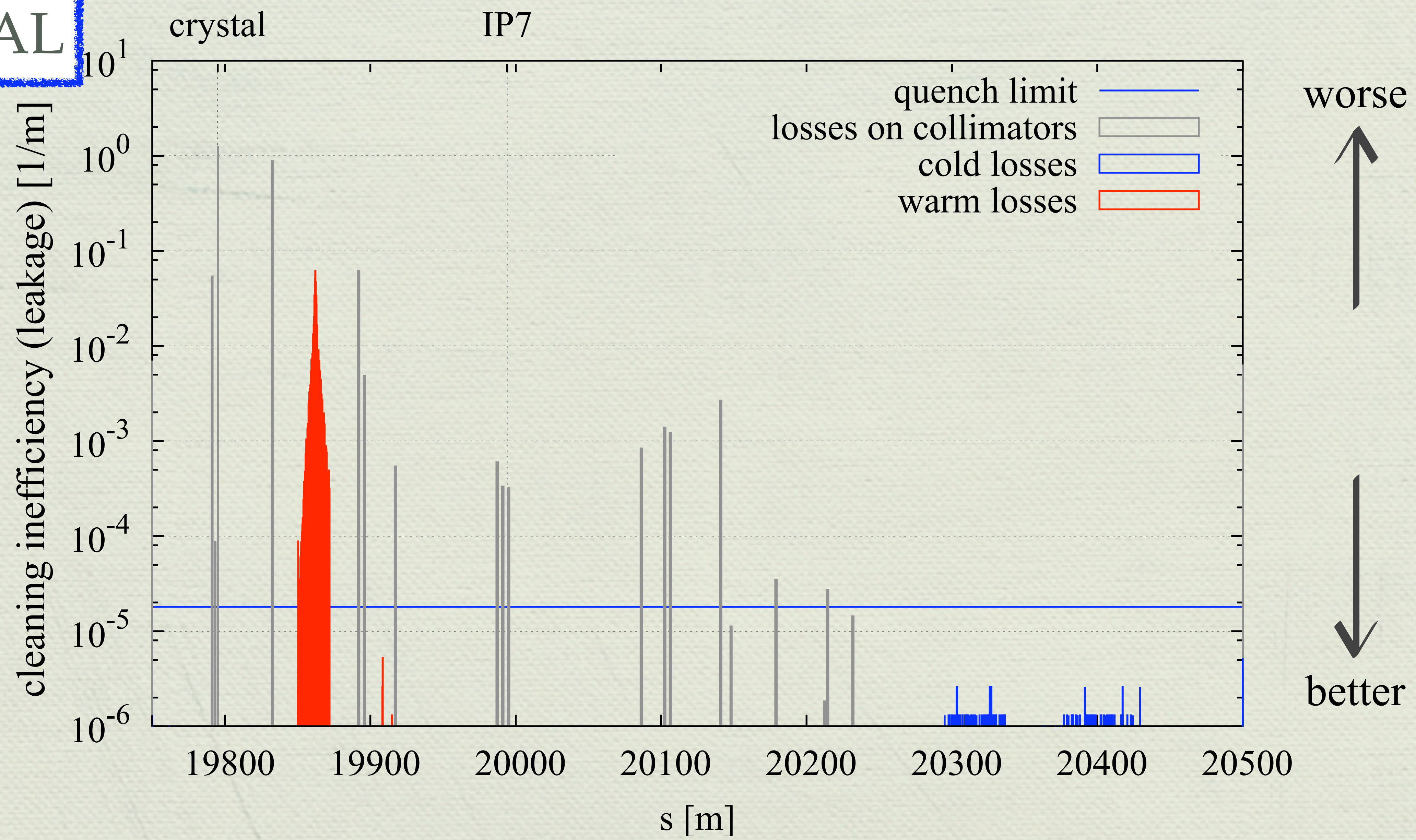
CRYSTAL



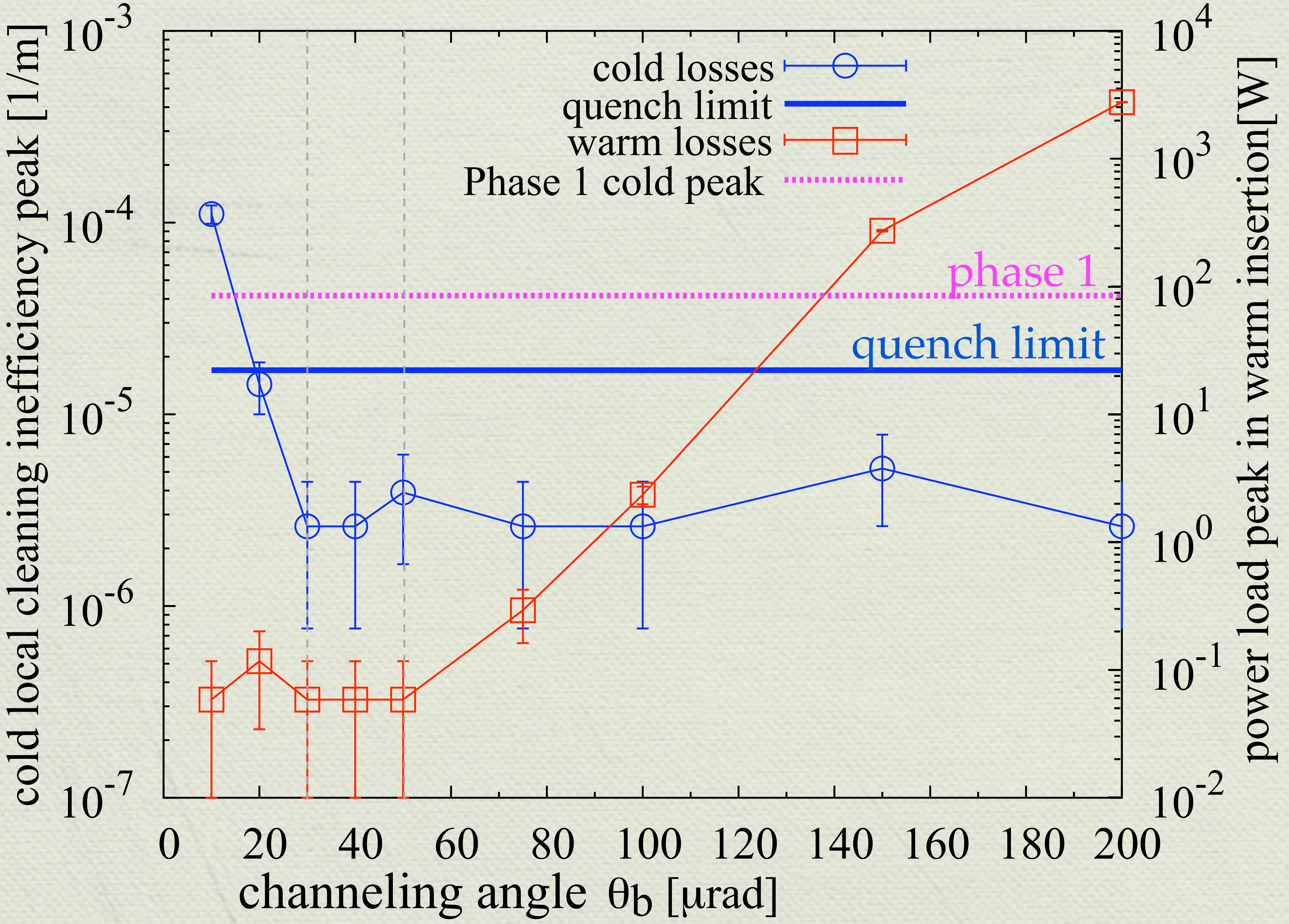
LHC loss maps - horizontal case

θ_b =200 μrad

CRYSTAL



LHC loss maps - summary for the horizontal case



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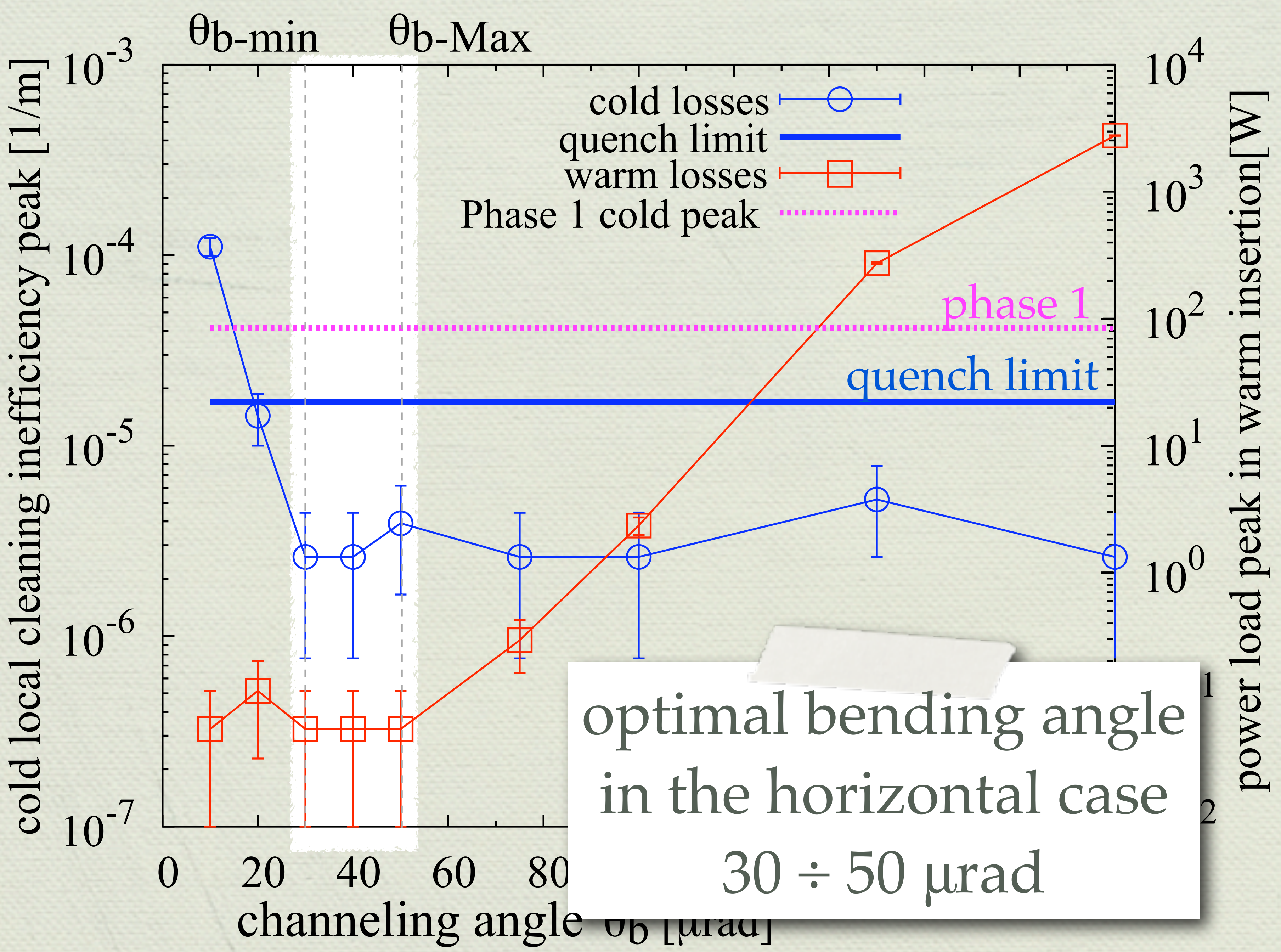
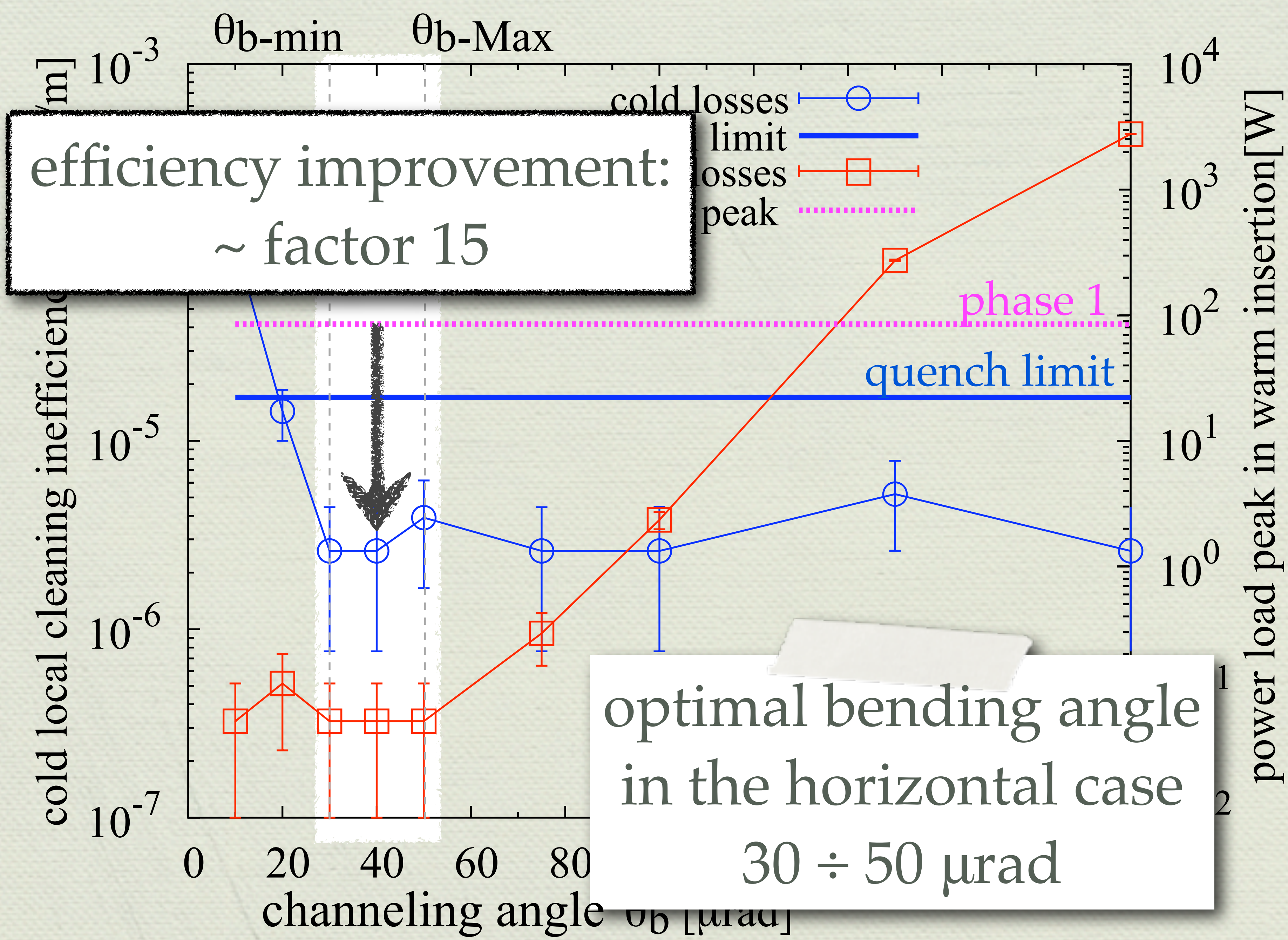
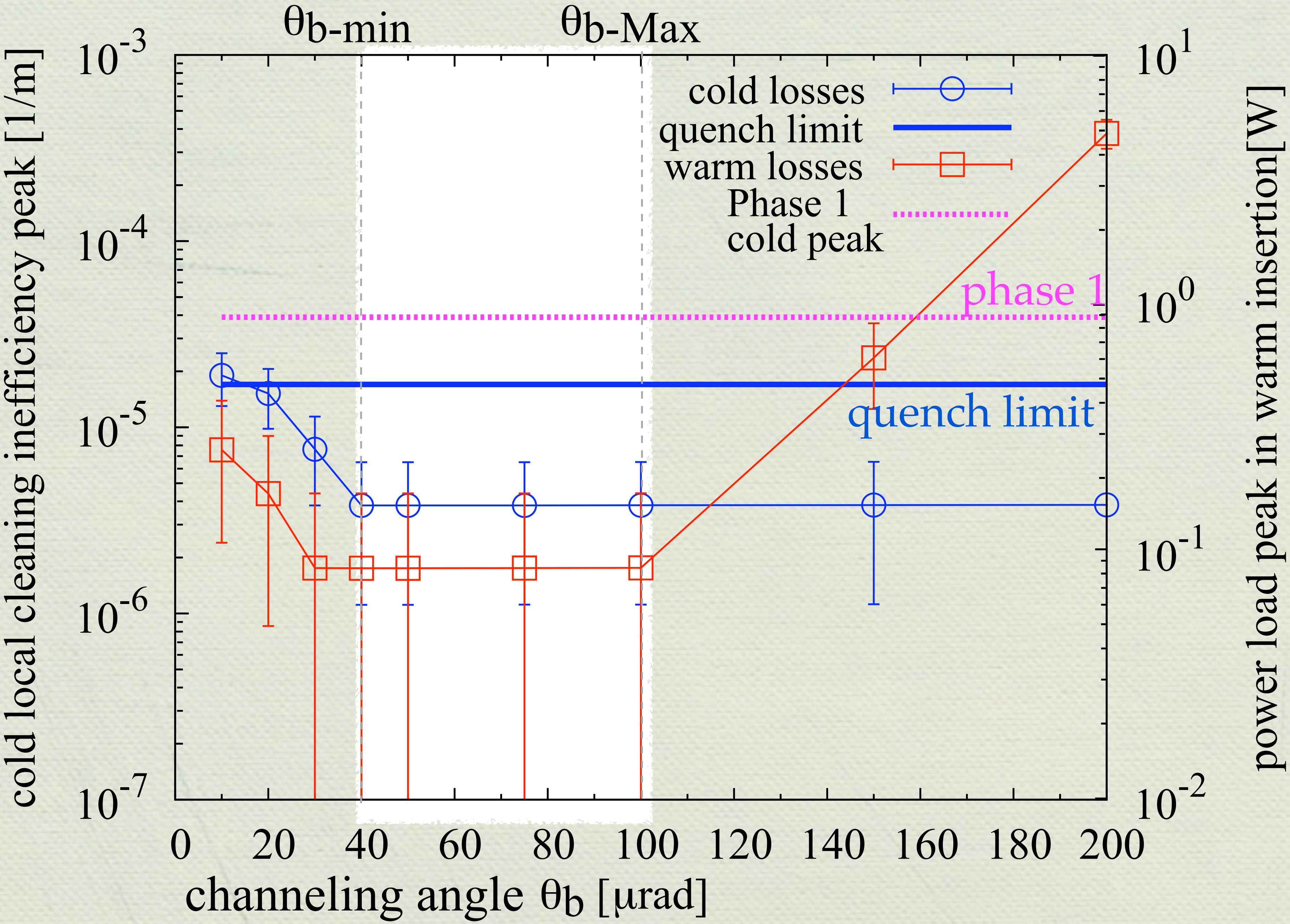


optimal bending angle in the horizontal case 30 ÷ 50 µrad

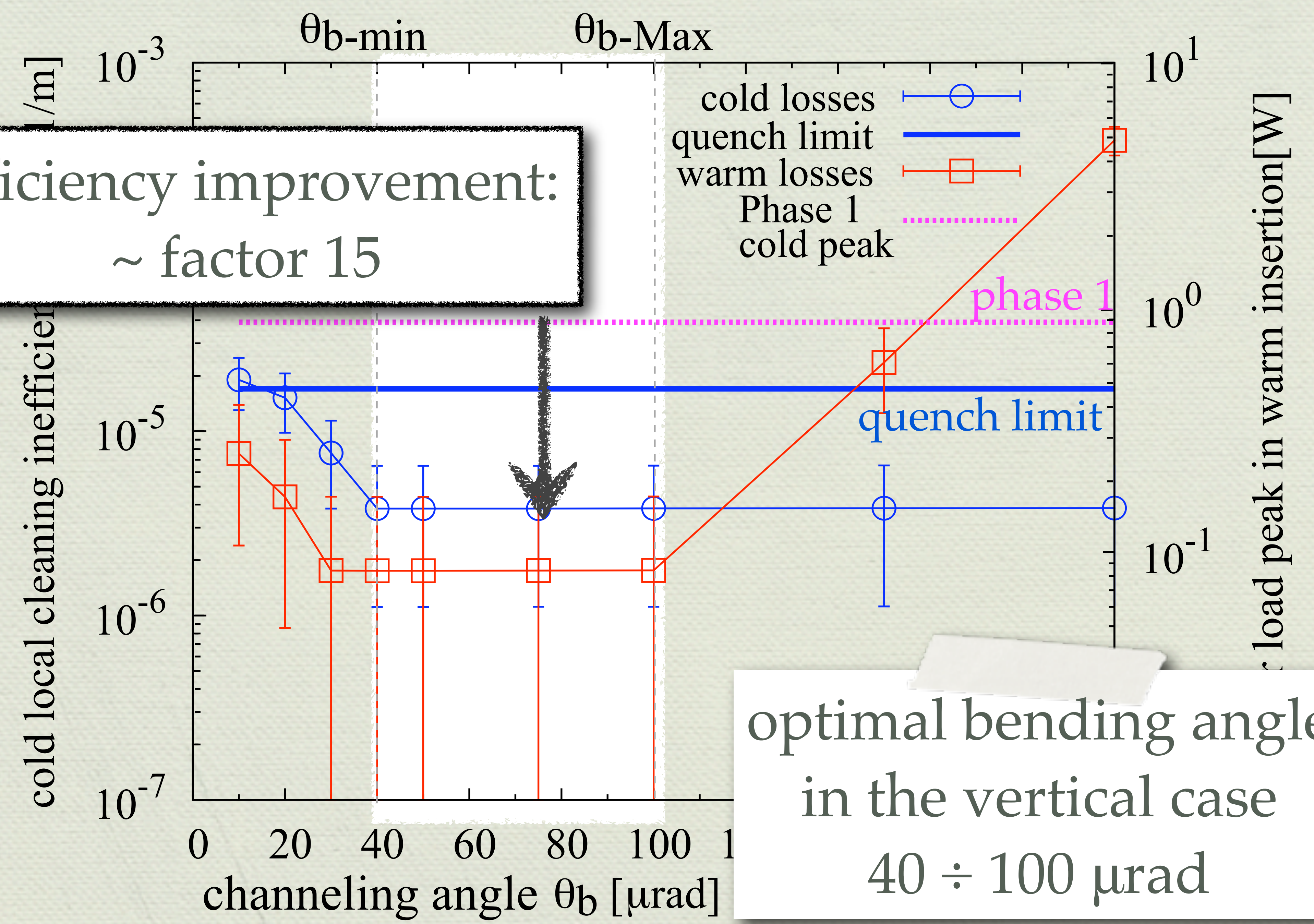
LHC loss maps - summary for the horizontal case



LHC loss maps - summary for the vertical case



LHC loss maps - summary for the vertical case



efficiency improvement:
~ factor 15

optimal bending angle
in the vertical case
40 ÷ 100 μrad

Conclusions

- The crystal collimation options has been considered for LHC, in case of stable physics beam at 7 TeV
- Dedicated tools have been developed:
  - theoretical tools: the grazing function formalism showed that the particle expected angular spread should be within the crystal angular acceptance
  - simulation tool: the state-of-the-art SixTrack code has been coupled with a MonteCarlo collimation code for the crystal. **The routine has been further developed**, inserting edge effects like amorphous layer and miscut angle
- The LHC crystal-enhanced collimation system has been simulated and optimized. A improvement factor 15 is predicted for optimal channeling angles ➔ **simulation results that will constitute an important benchmark for future experimental results**

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- Th
  im
  res **ts**

simulation predictions for SPS in 2009 (both for channeling and collimation efficiency) were a factor 10 higher than measured! Priority is demonstrate that we can reach in experiment the performances predicted by simulations/or to find what is missing in our model...

this work was possible thanks to the effort of many people. I especially would like to thank:

- my **EPFL supervisor** L. Rivkin
- present and past people in the **CERN collimation team**

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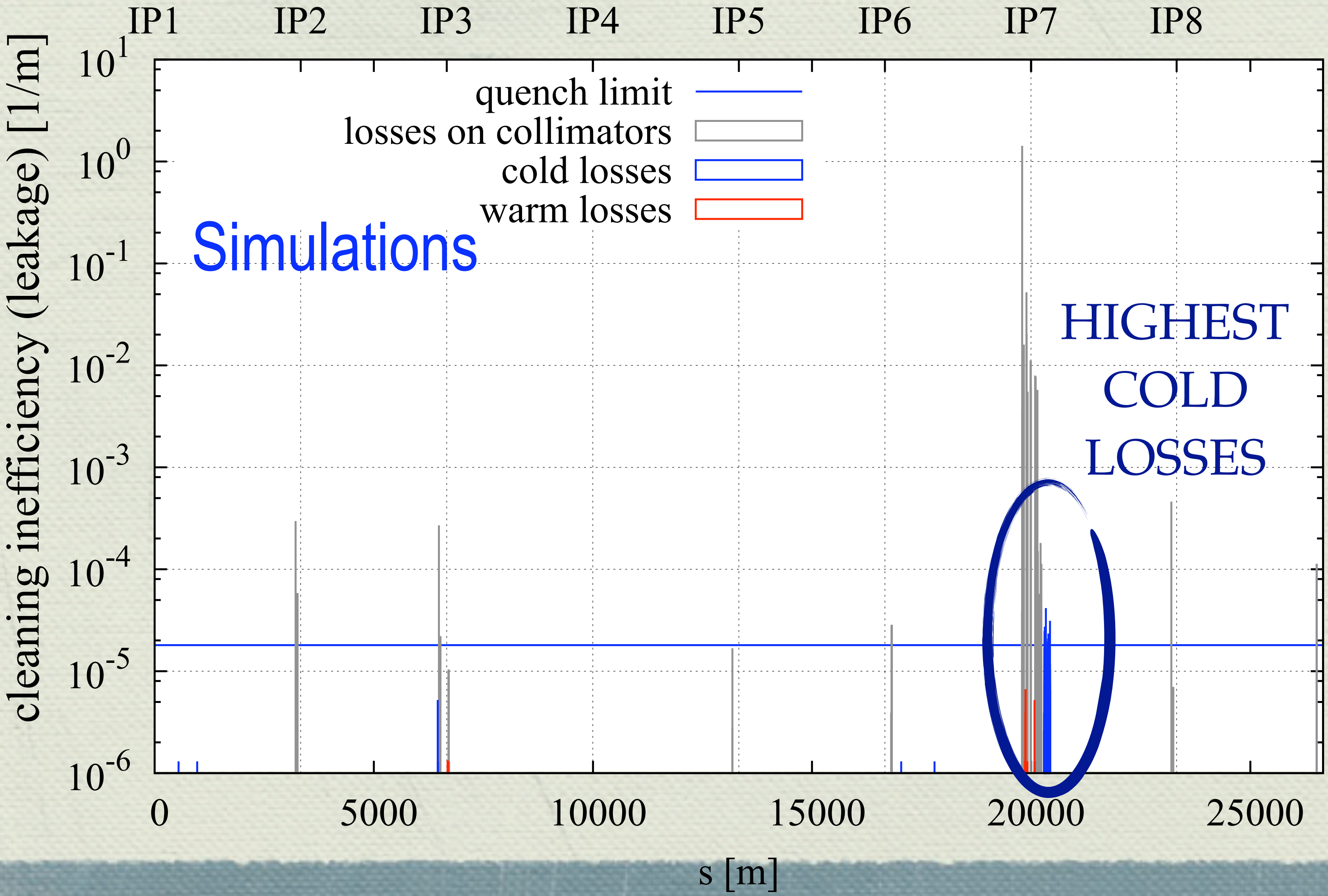
- **colleagues in Fermilab**

N. Mokhov, V. Shiltsev, D. Still, R. Carrigan, J. Annala

reserve slides

... but still limited!

basic limitation of the collimation system: losses receiving a small kick but a non negligible $\Delta p/p$ escape the collimation insertion but are immediately lost at the first bending magnets

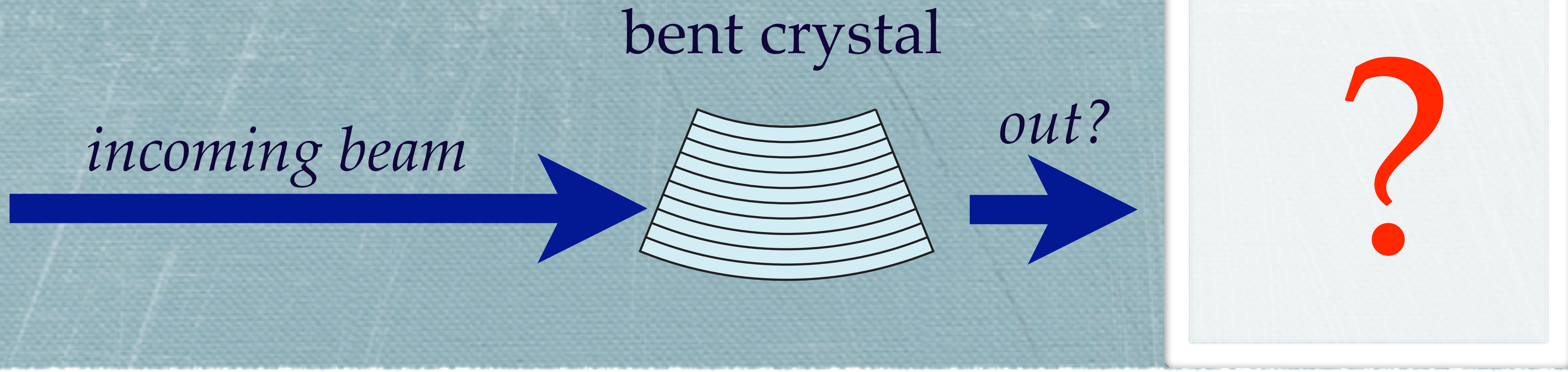


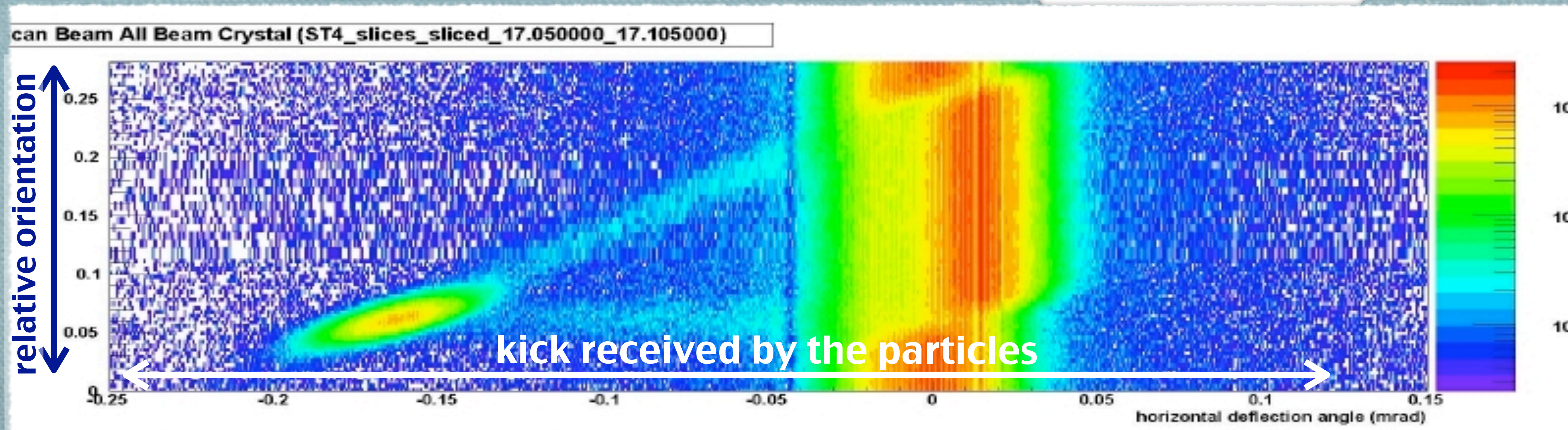
Beam Loss Maps

local collimation cleaning inefficiency η_{loc} vs longitudinal coordinate s

main simulation outcome!

a system of dedicated BLMs are positioned along the full SPS ring (one each quadrupole). The same is for LHC. Beam Loss Maps can be obtained and compared with the simulation results.

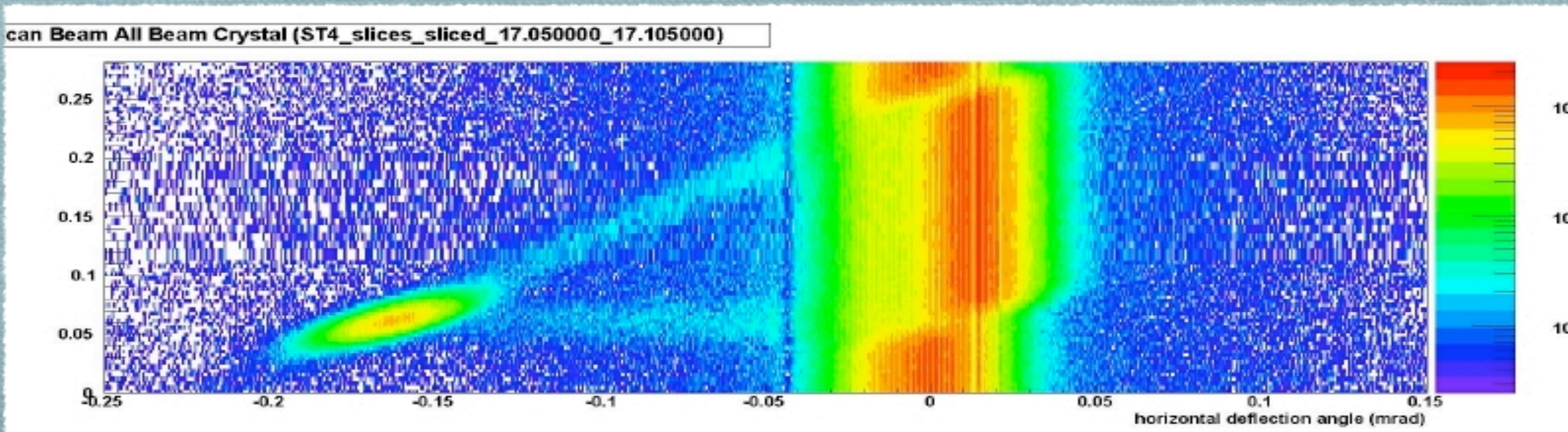




courtesy of W. Scandale

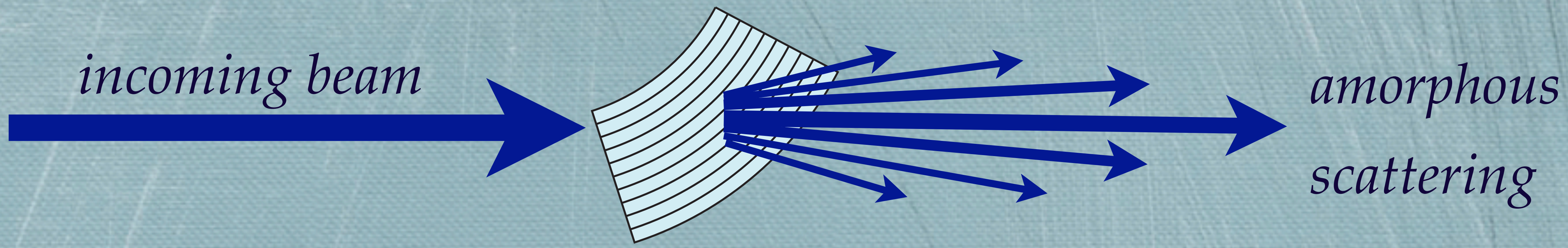
how does a crystal work?

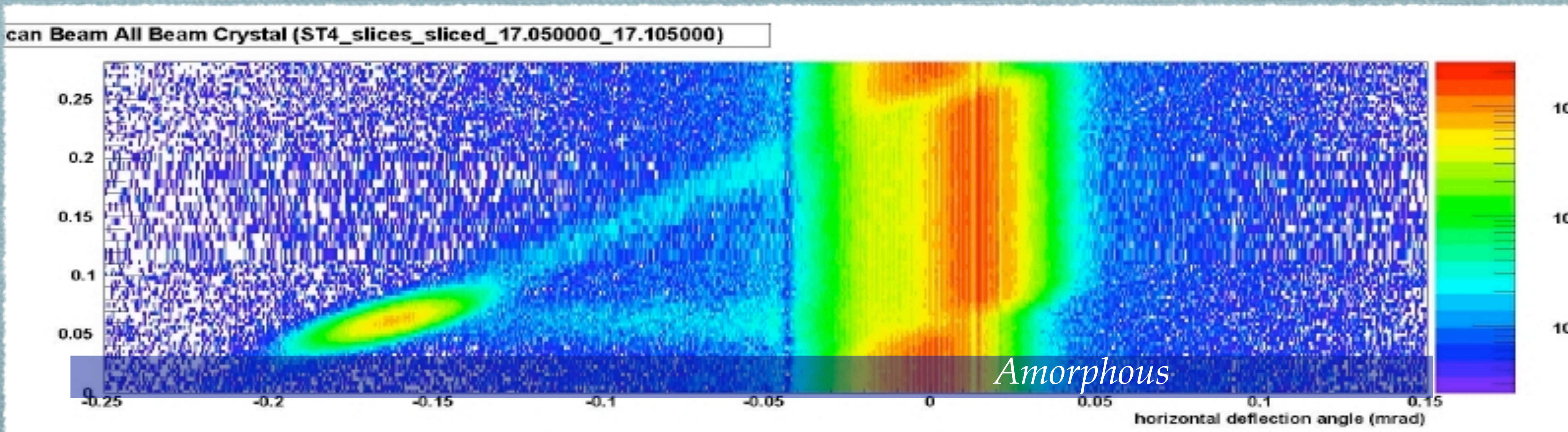
it depends on the crystal-beam relative orientation!



courtesy of W. Scandale

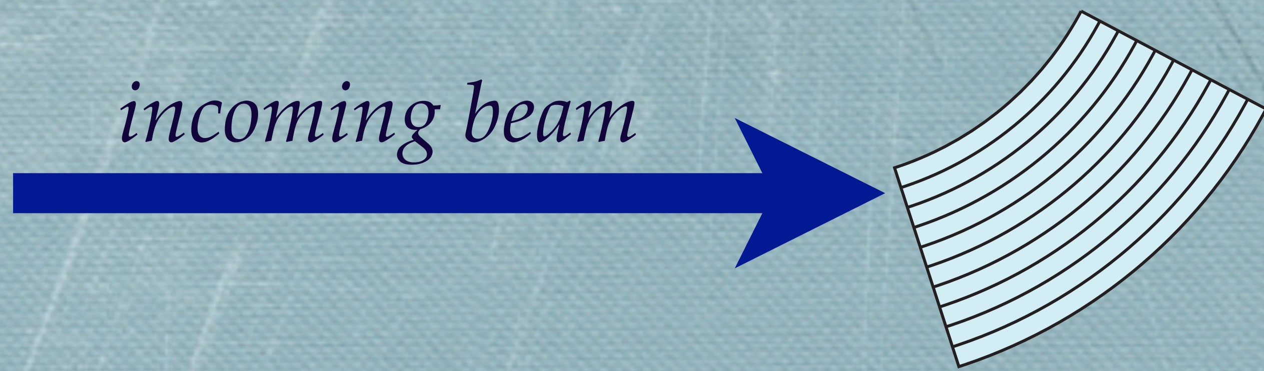
how does a crystal work?
Amorphous mode

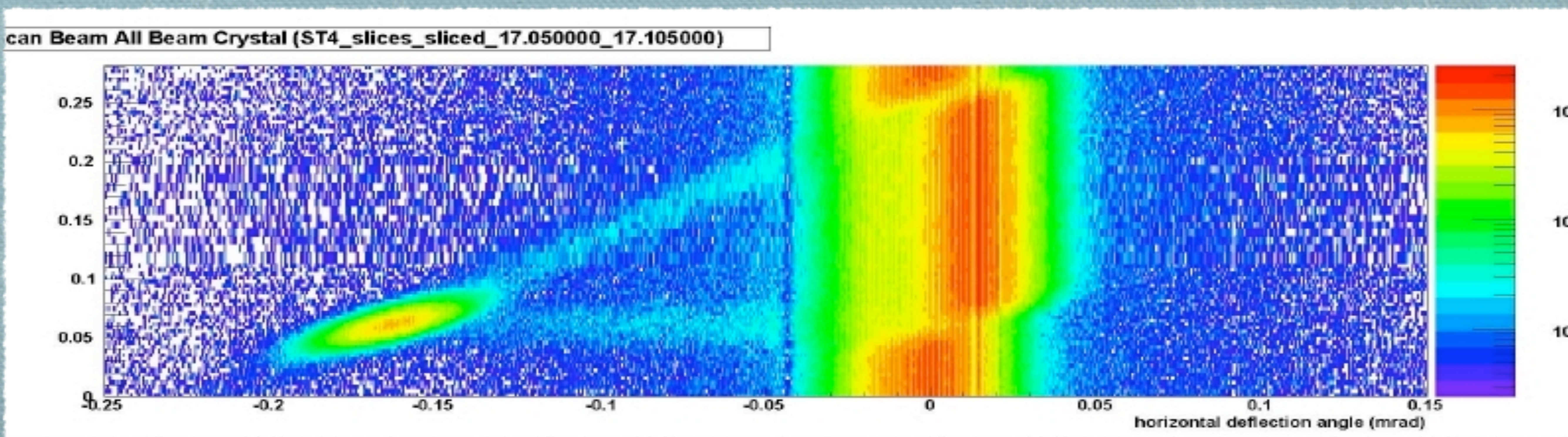




courtesy of W. Scandale

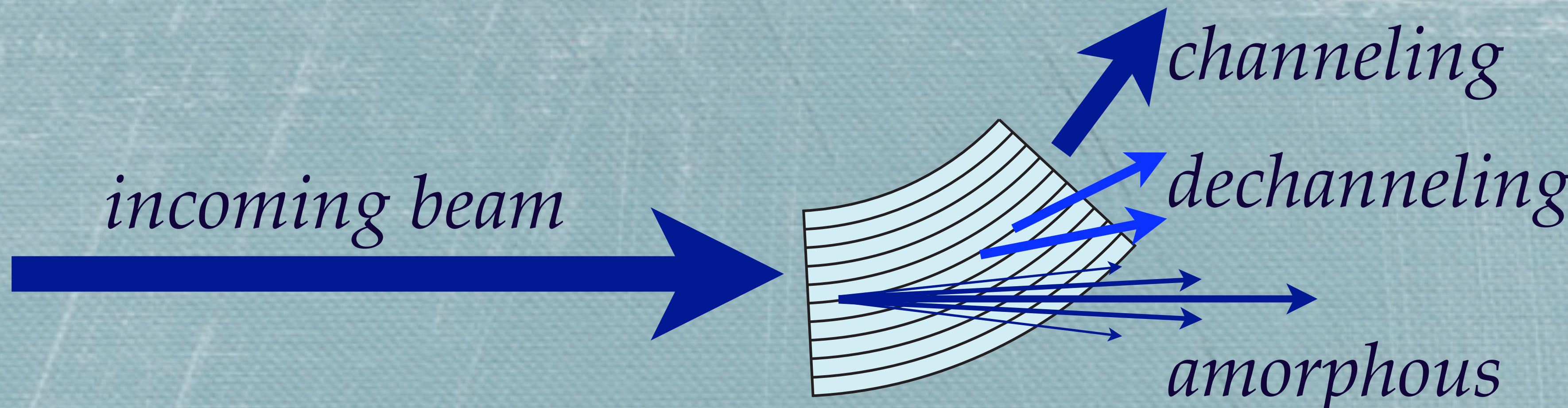
how does a crystal work? Amorphous mode



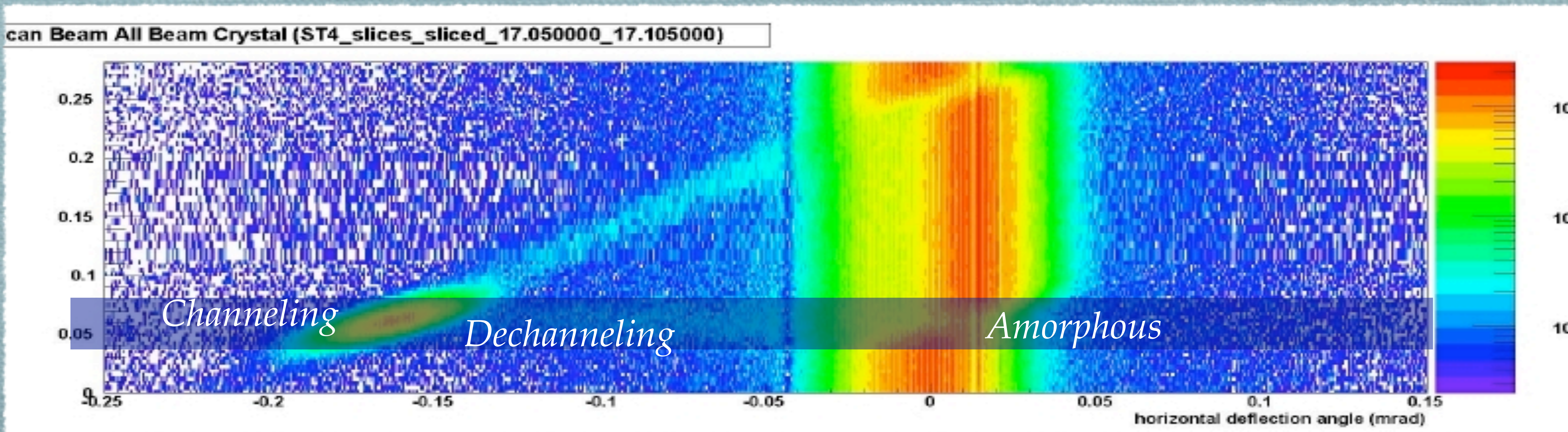


courtesy of W. Scandale

how does a crystal work? Channeling mode

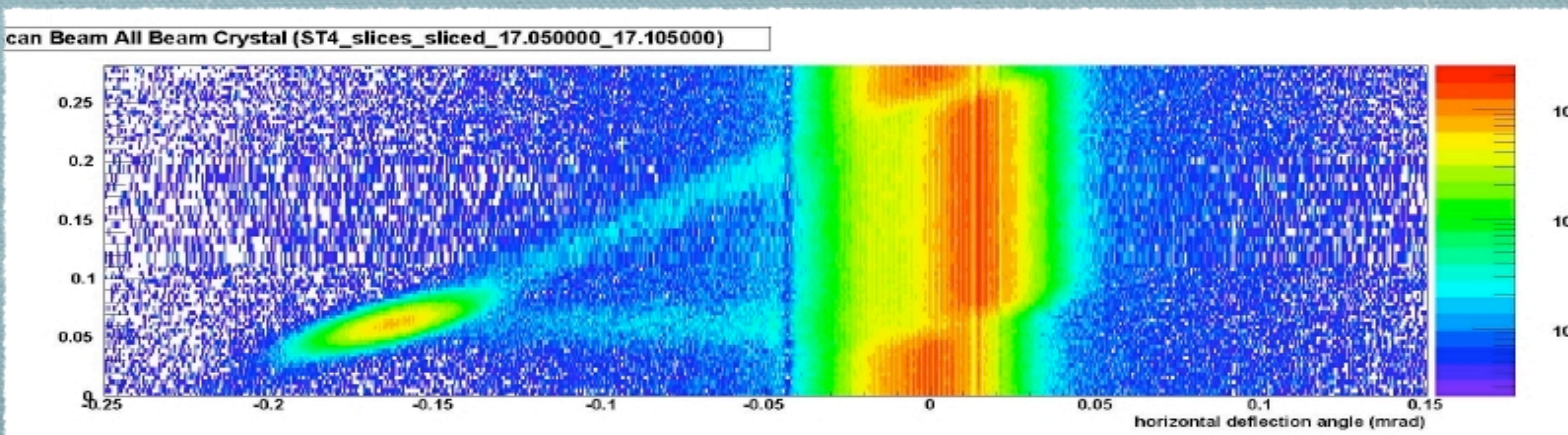


Channeling
- efficiency: 50%
- kick:100-500 urad
- acceptance: 2-20 urad
(depends on energy)



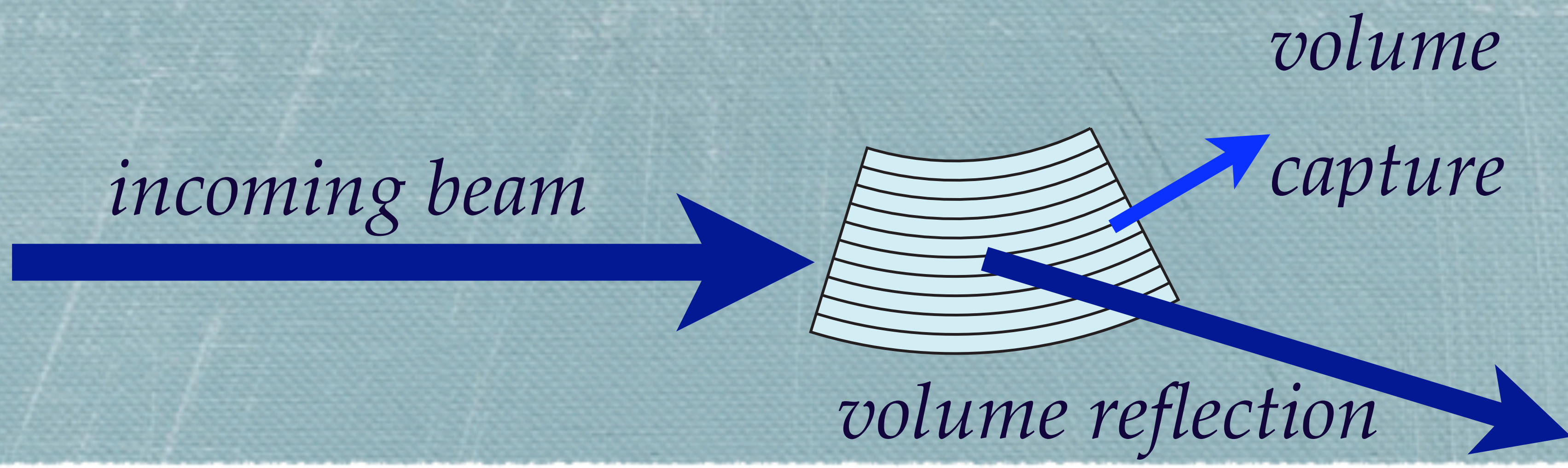
courtesy of W. Scandale

how does a crystal work? Channeling mode



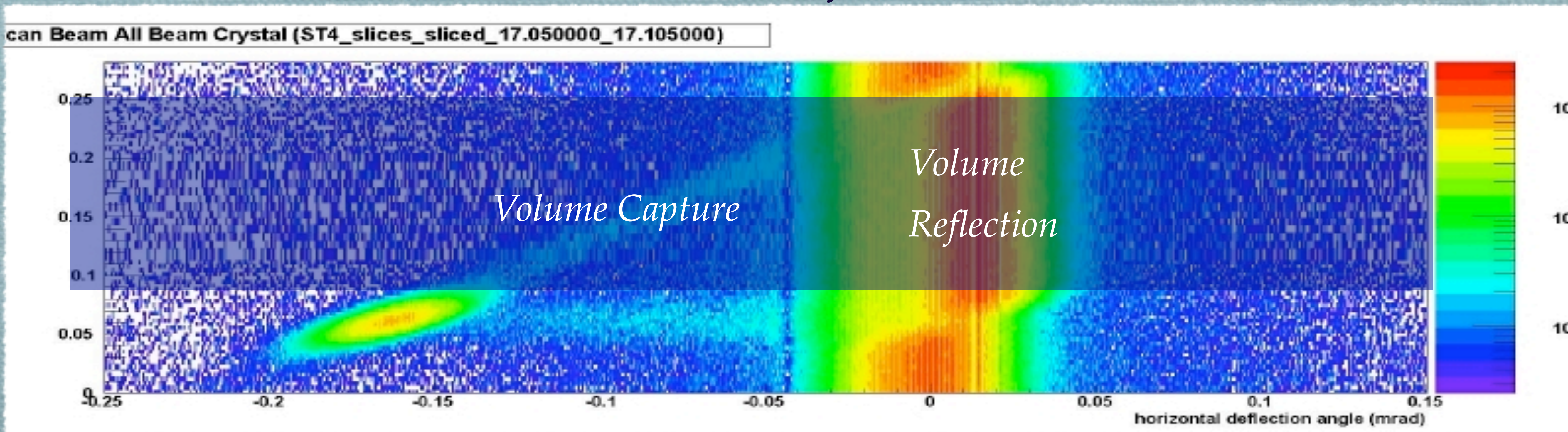
courtesy of W. Scandale

how does a crystal work? Volume Reflection mode



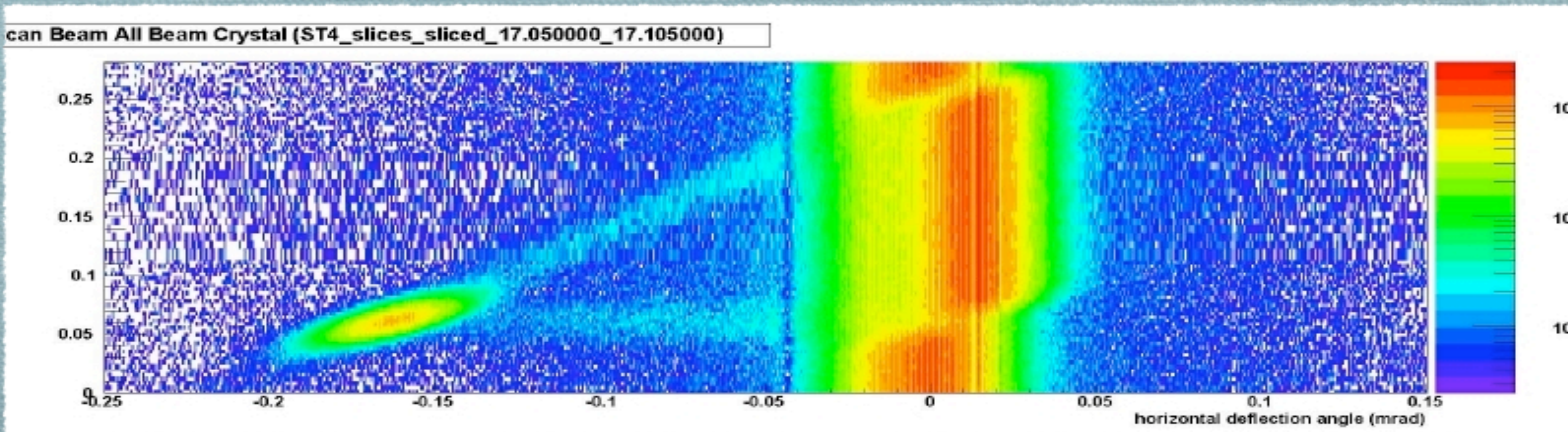
Volume Reflection

- efficiency: 99%
- kick: 2-20 urad
(depends on energy)
- acceptance: 100-500 urad



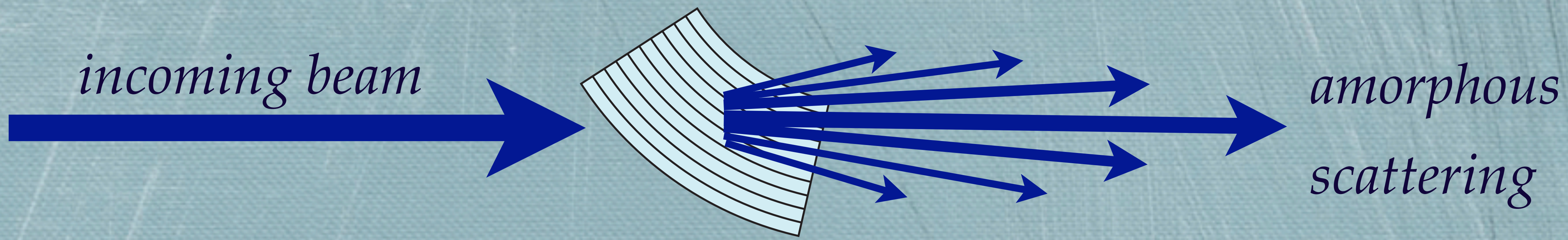
courtesy of W. Scandale

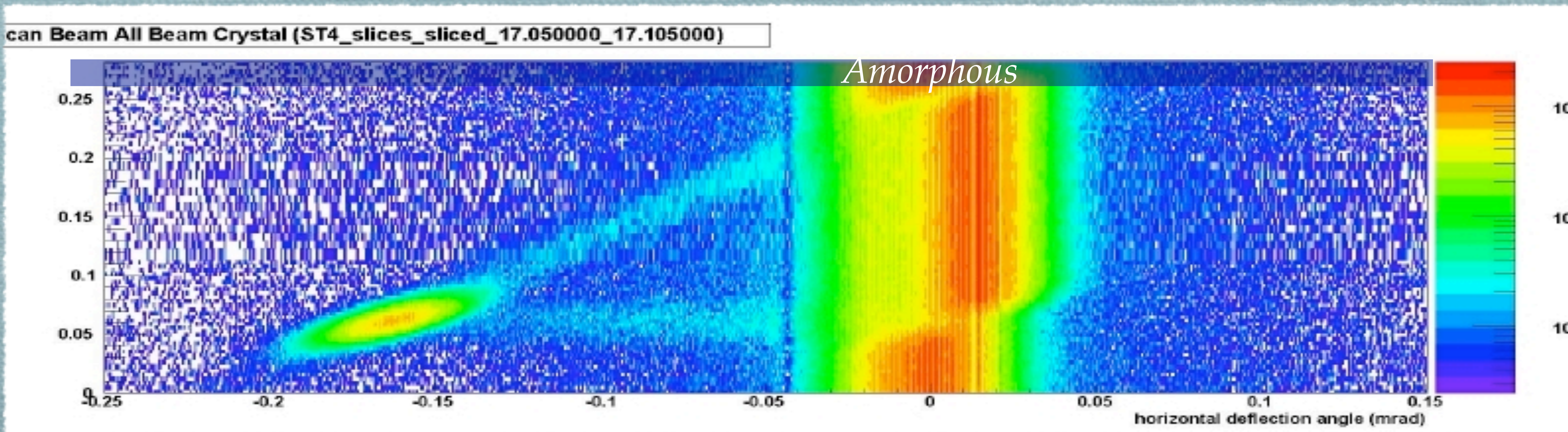
how does a crystal work?
Volume Reflection mode



courtesy of W. Scandale

how does a crystal work? Amorphous mode

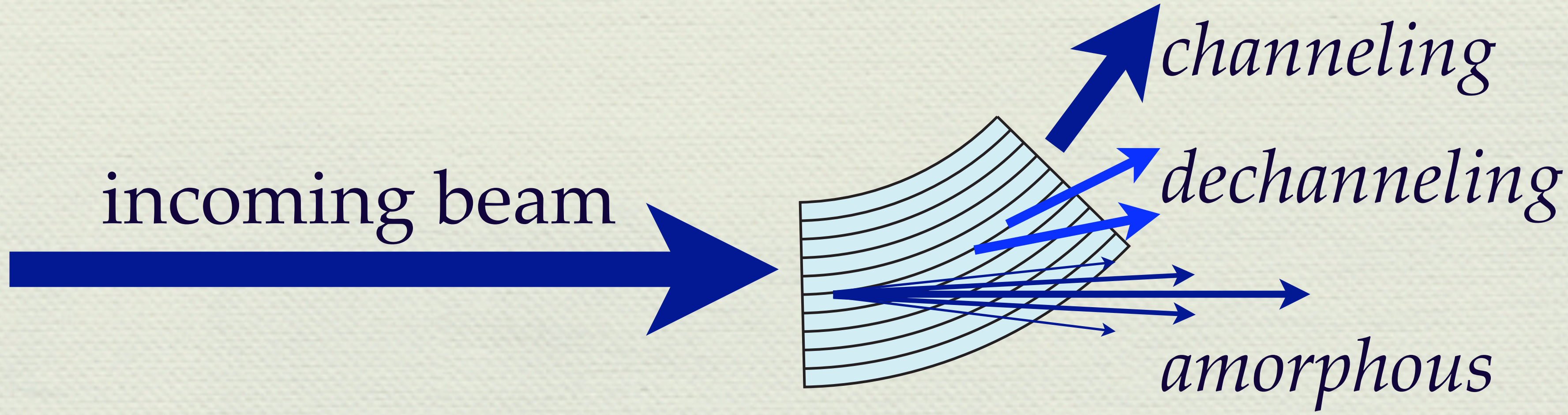




courtesy of W. Scandale

how does a crystal work? Amorphous mode

Channeling mode



Channeling

- efficiency: 50%
- kick:100-500 urad
- acceptance: 2-20 urad

(depends on energy)

$$\frac{pv}{2}\theta^2 + U(x) < U_0$$

$$U_{eff}(x) = U(x) + \frac{pv}{R}x$$

for the bent crystal, the effective potential is slightly reduced by a centrifugal term