Concept of a Collimation System with Enhanced Operational Stability and Performance

Accelerator Research and Development
ARD
A program by the Helmholtz association

R.W. Aßmann

Leading Scientist DESY

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HELMHOLTZ
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European Network
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for Novel Accelerators

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DESY

Why this talk?

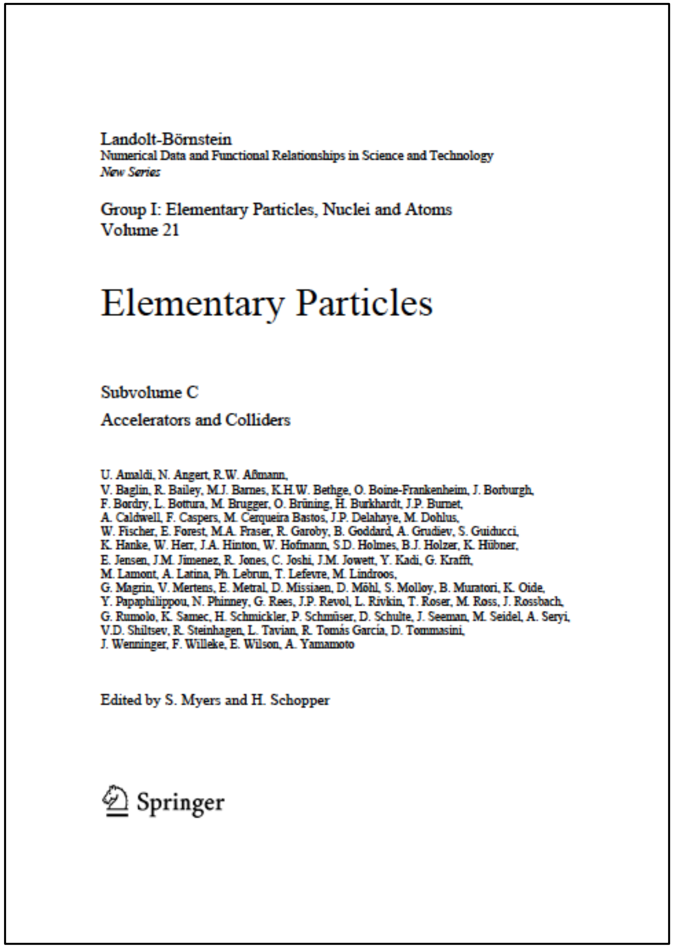
1. FCC is an **important study and collimation will be one of the critical issues** for its success.
2. I was in charge of LHC collimation from 2002 to 2012, as the responsible CERN physicist for designing, constructing, installing and commissioning the system (“collimation project leader”).
3. Our **LHC collimation solution and system worked very well**, fully consistent with simulations done years before.
4. I still have some **non-studied ideas and concepts for hadron collimation** in my head. Would be nice to see some study…
5. You know Michael: He is a **very convincing person** who asked me so kindly that I could not refuse…

DISCLAIMER: DESY has no responsibility for FCC collimation, nor do we have presently or in the foreseeable future any resources in my team to get involved. Still very happy to advise on an occasional basis …

This Time My Last Collimation Talk?

- Thanks to the colleagues, many of them good friends, who worked with me for many years on collimation at CERN.
- Thanks to my former students and fellows.

LHC sytem is published and well documented…



Landolt-Börnstein
Numerical Data and Functional Relationships in Science and Technology
New Series

Group I: Elementary Particles, Nuclei and Atoms
Volume 21

Elementary Particles

Subvolume C

Accelerators and Colliders

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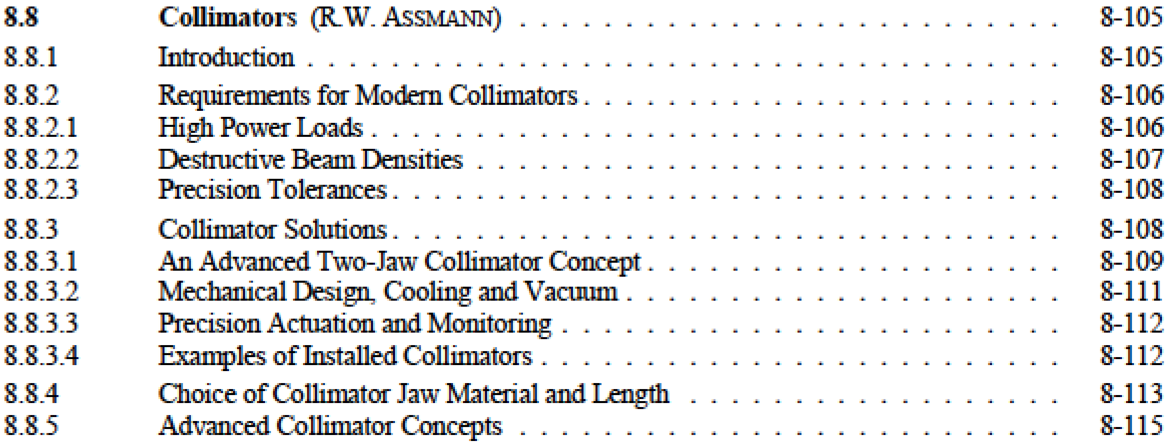

Section '8.8 Collimators' of the Chapter '8 Accelerator Technology'. **Landolt-Börnstein - Group I Elementary Particles, Nuclei and Atoms. Subvolume C 'Accelerators and Colliders' of Volume 21** 'Elementary Particles' of Landolt-Börnstein - Group I 'Elementary Particles, Nuclei and Atoms'.

7 TeV → 50 TeV: EASY?

- Stored energy: 360 MJ → 8,000 MJ

Peak losses for below 1 s

- Loss rate (peak): 0.14 %/s → 0.14 %/s
- Loss power (peak): **500 kW** → **11,000 kW**

Peak losses for below 1 s

- Loss rate (for 10s): 0.06 %/s → 0.06 %/s
- Loss power (for 10s): **200 kW** → **4,400 kW**

During losses operational conditions must be maintained: **no quench, good vacuum = low collimator jaw temperature, efficient collimator cooling, good geometrical stability collimator surface, survival RF fingers, low power load to surrounding equipment, …**

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Peak losses f

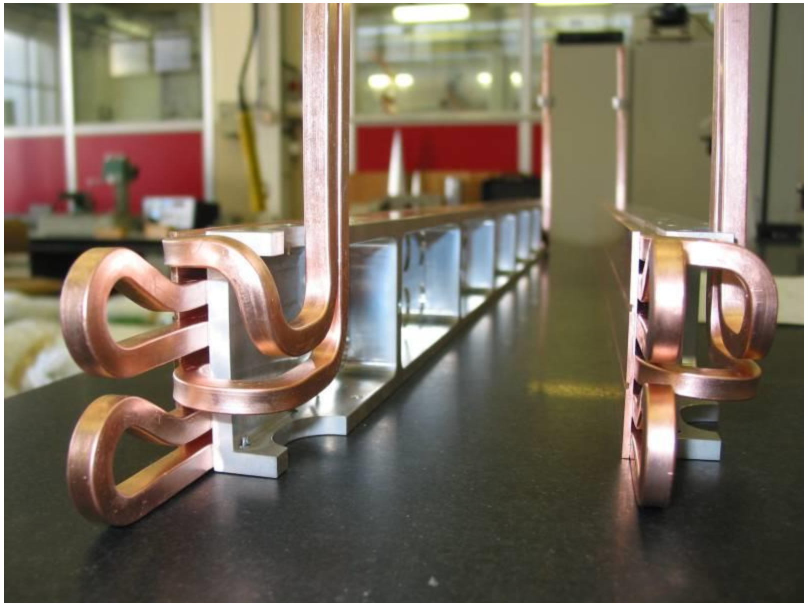
		→	0.06 %/s
	0 kW	→	4,400 kW

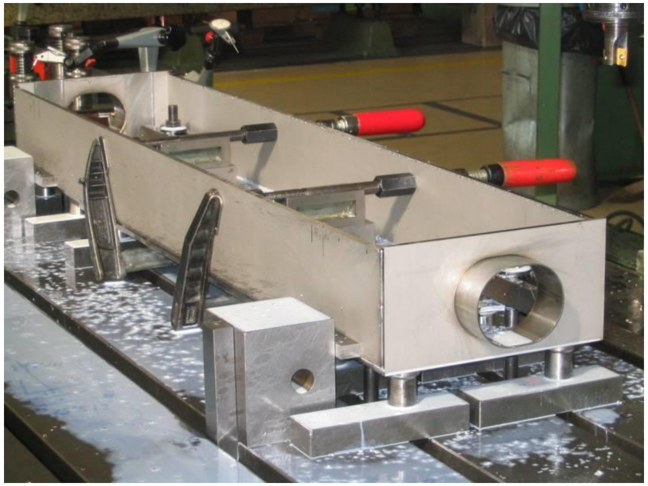
It took us years to solve this for the LHC → Difficult!

During losses operational conditions must be maintained: **no quench, good vacuum = low collimator jaw temperature, efficient collimator cooling, good geometrical stability collimator surface, survival RF fingers, low power load to surrounding equipment, ...**

Heavily Cooled High-Power LHC collimator

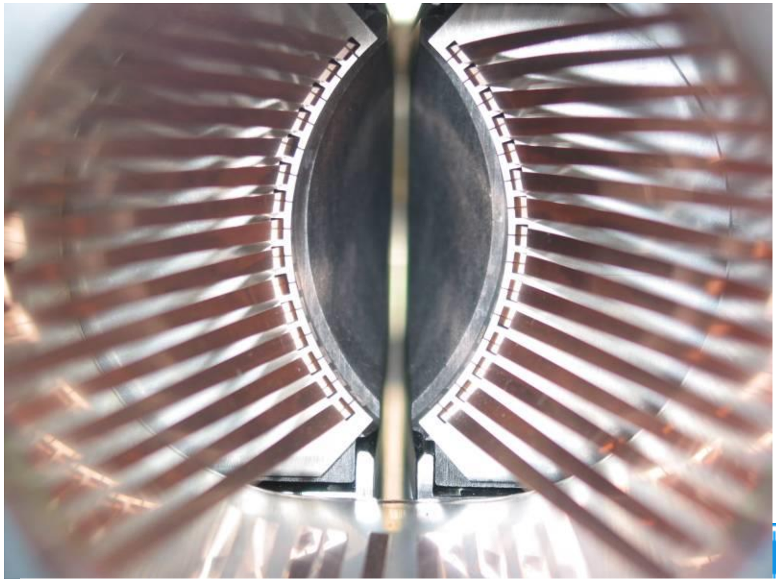
Jaw
clamping
support
with
cooling





Vacuum
tank

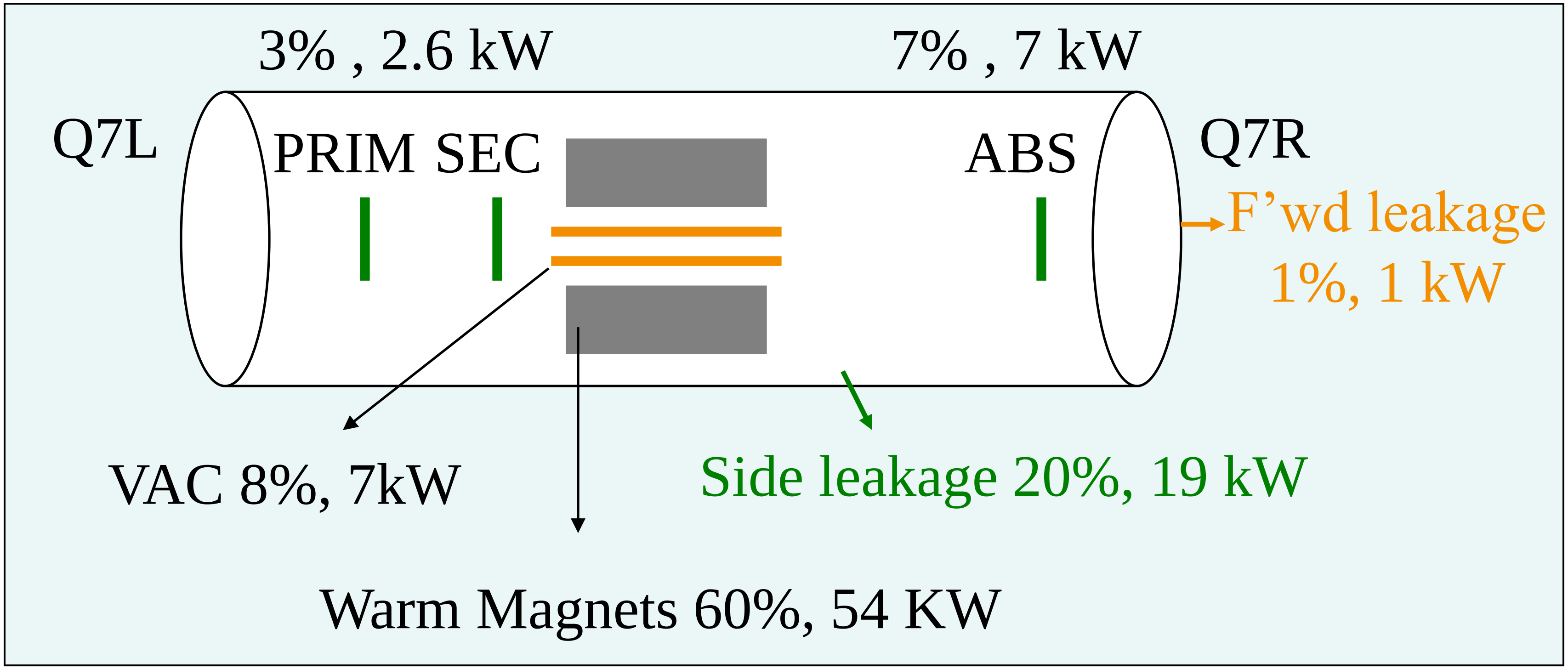
Completed
jaw



Beam passage for small collimator gap with
RF contacts for guiding image currents

R. Assmann

EXAMPLE: Power flow IR3, τ = 1h , P_{tot} = 90kW

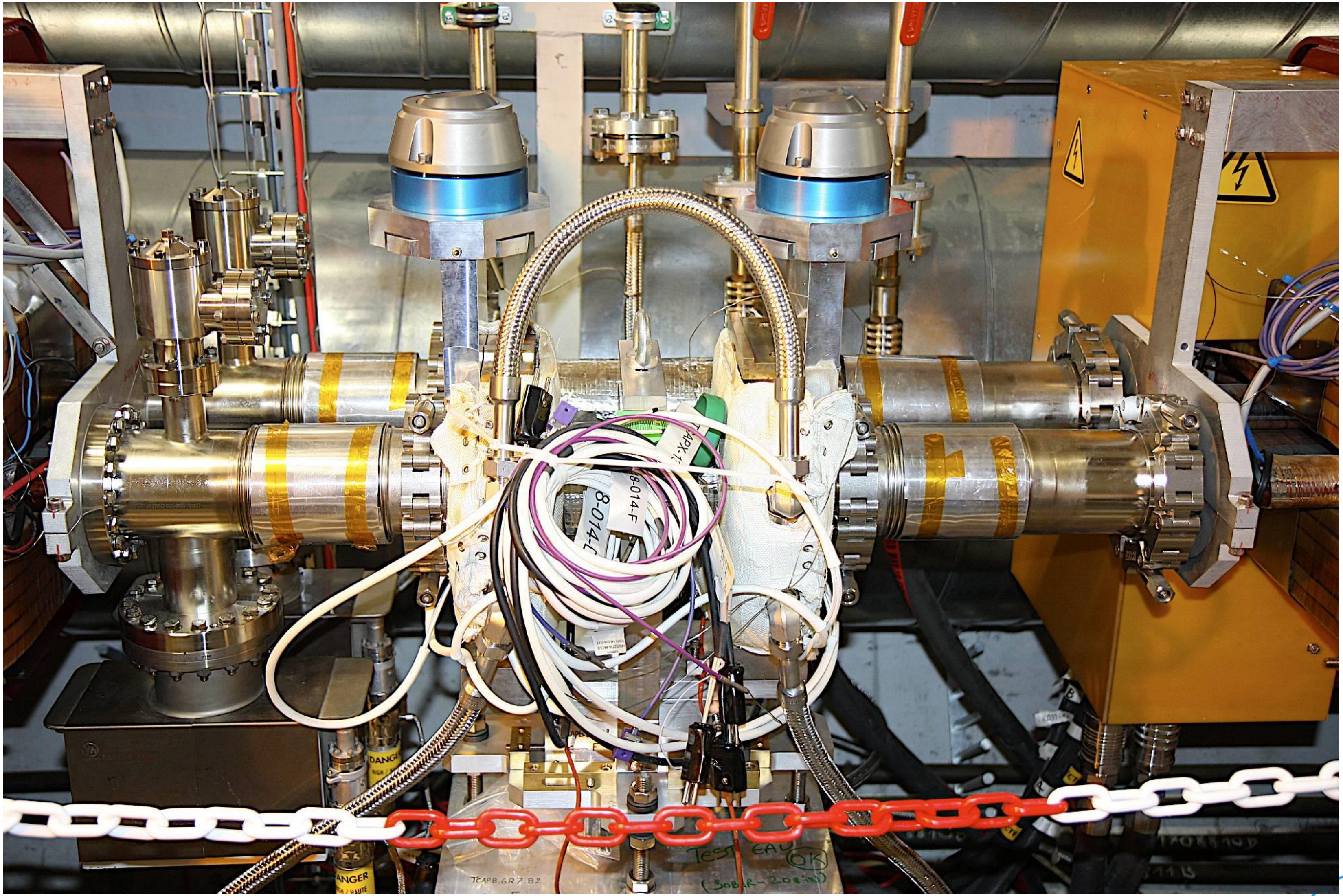


J.B. Jeanneret, I. Baishev

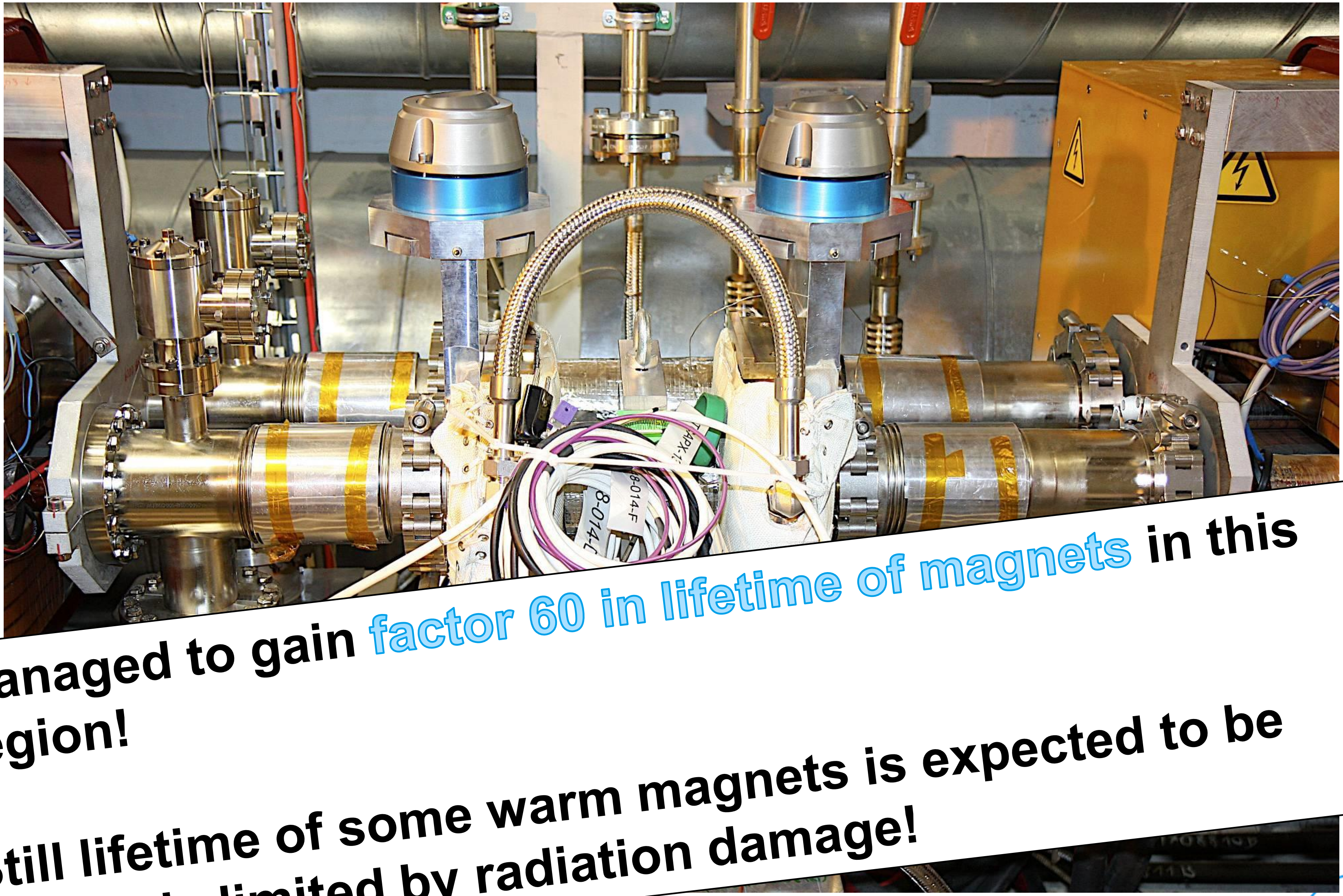
- Need **active and passive absorbers** to limit load on auxiliary systems
- Consequences for vacuum ...

R. Assmann

The Real Hero of LHC Collimation: TCAPA…



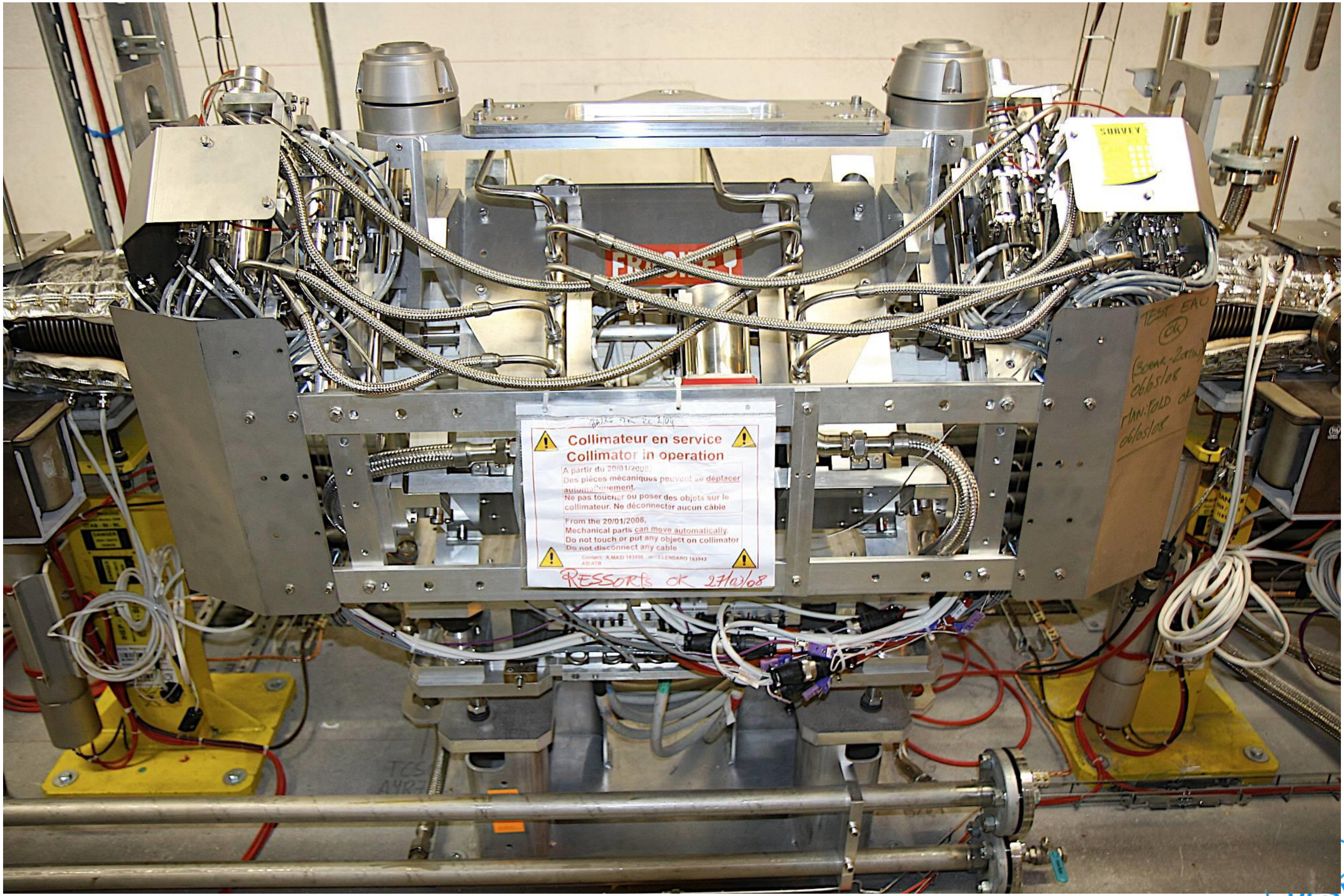
The Real Hero of LHC Collimation: TCAPA…



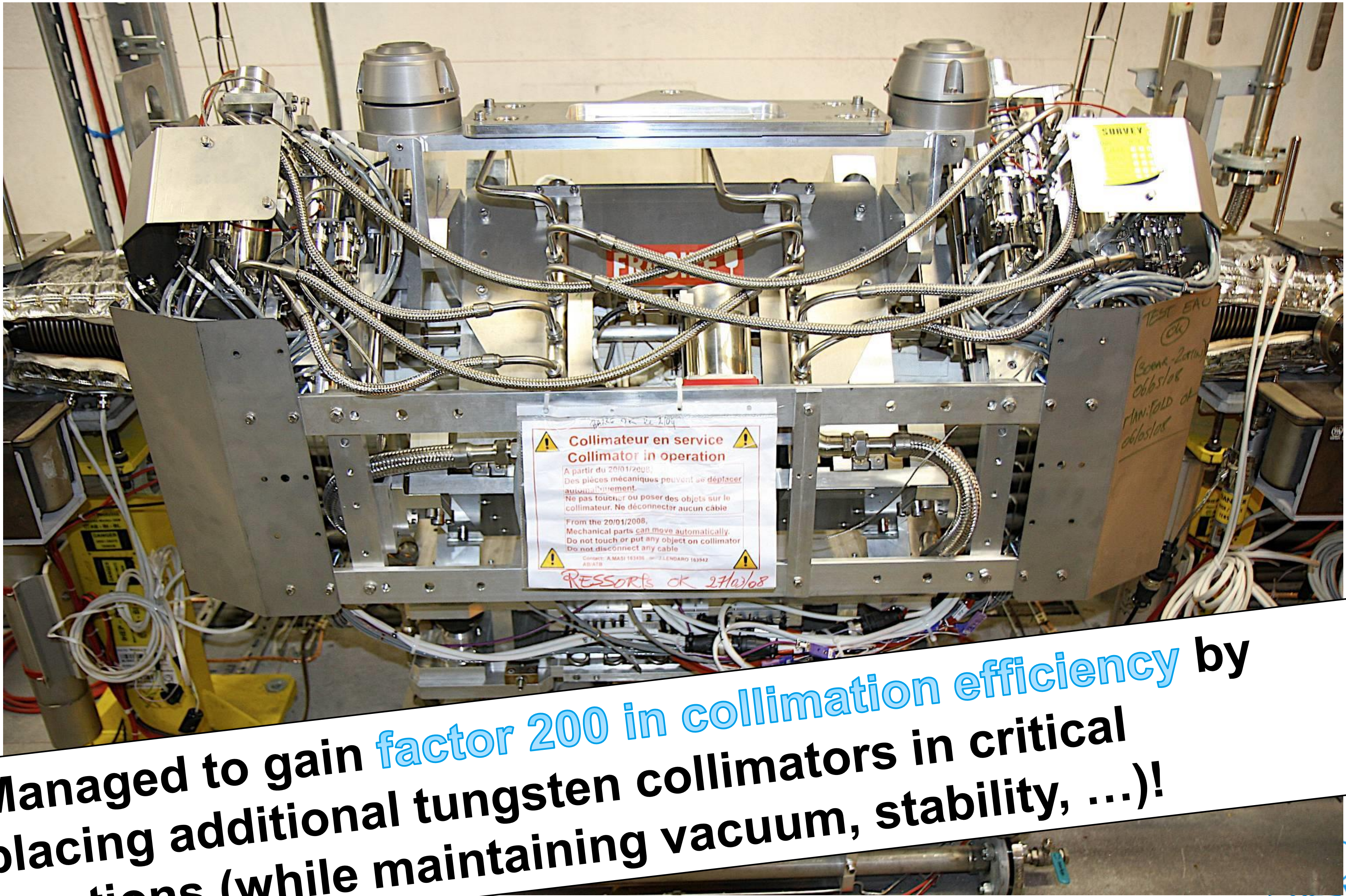
Managed to gain factor 60 in lifetime of magnets in this region!

Still lifetime of some warm magnets is expected to be seriously limited by radiation damage!

The workhorse LHC collimator…



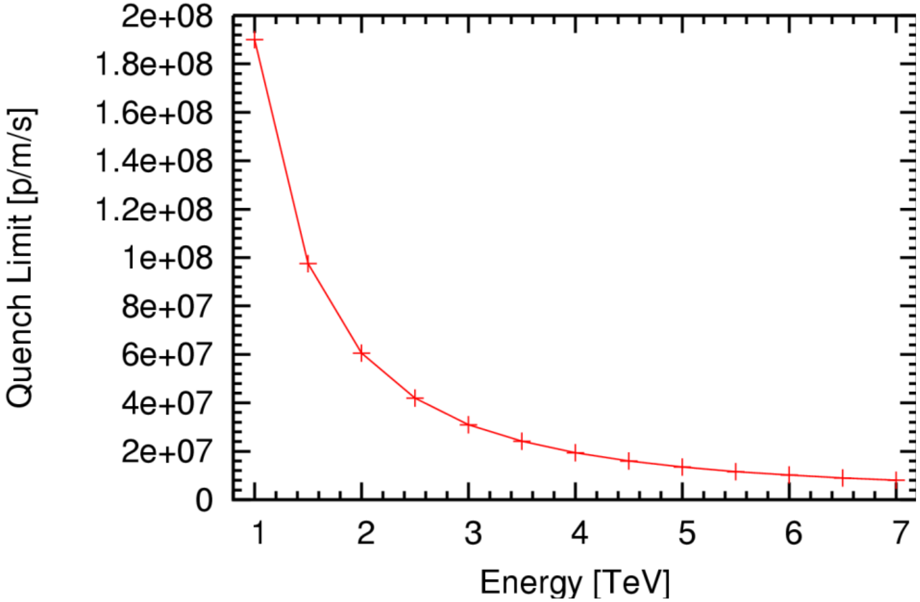
The workhorse LHC collimator…



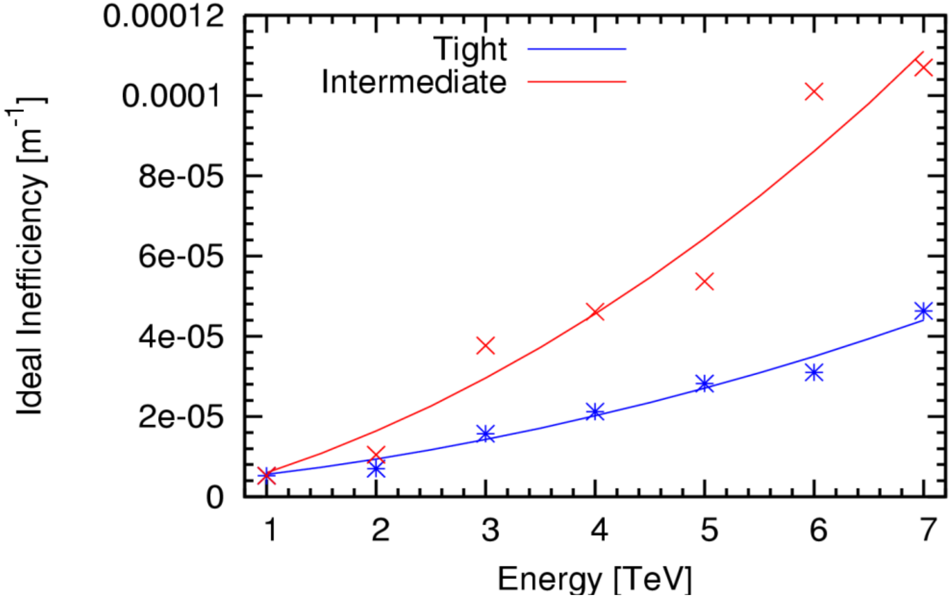
Managed to gain factor 200 in collimation efficiency by placing additional tungsten collimators in critical locations (while maintaining vacuum, stability, …)!

How will LHC Collimation Behave at High Energy?

Quench Limit LHC Magnets



Leakage LHC Collimation



4 TeV → 7 TeV → 50 TeV

2.0e-4 (1/m) → 4.4e-4 (1/m) → ≈ 50 – 100 e-4 (1/m)

Extrapolation very uncertain, just based on simulations from 1 TeV to 7 TeV!

WHY? It is the Physics: Comparing MCS and SD processes I

Parameter	MCS	SD
Energy E	~ 1/E	~ ln (E)
Length L	~ √L	~ L

MCS brings p from primary to secondary collimator:

- Imagine going from E0 to E1 in energy.
- Typical scattering angle: $\theta_1 = \theta_0 * E_0 / E_1$
- Required scattering angle: $\theta_{1,req} = \theta_{0,req} * \sqrt{(E_0 / E_1)}$
- For required scattering angle travel longer length:

$$L_1 = L_0 * \sqrt{(E_1 / E_0)}$$

Comparing MCS and SD processes II

Now SD (single diffractive) scattering:

- Length traversed: $L_1 = L_0 * \sqrt{}(E_1 / E_0)$ (from MCS)
- Cross section: $\sigma_1 = \sigma_0 * \ln(0.3*E_1) / \ln(0.3*E_0)$
- Probability for SD scattering with MCS scaling:

$$P_1 = P_0 \cdot \frac{\sqrt{E_1} \cdot \ln\left(0.3 \cdot E_1\right)}{\sqrt{E_0} \cdot \ln\left(0.3 \cdot E_0\right)} \qquad \text{with } E_1 > E_0$$

- Effects from SD scattering become stronger with higher beam energy.
- Loss from 7 TeV to 50 TeV: **factor 9.8**

Situation More Complicated (of course)

- Multi-turn behavior not so simple to just linearly add up kicks (as assumed before).
- It is not fully correct to express the transport from primary to secondary collimator by a required kick (diffusion process).
- Single-diffractive scattering and MCS produce combined effects.
- Other processes play into the game.
- **Still a very useful analytical estimate…**

So for the 50 TeV FCC collider…

- Power loads on collimators reach **10 MW regime**
- Quench limits for a given magnet design fall quickly with beam energy → are the **high field magnets more tolerant to beam-induced heating**?
- Collimation **efficiency worse by factor > 10 due to different balance of physics processes**, in particular multiple coulomb scattering (MCS) to single diffractive scattering (SD)…

A new design should make use of all possible measures to arrive at the best possible system.

A number of (I believe) **good ideas exist from the LHC design work. We could not implement them as it was too late when I got involved.**

Not properly published or only partially published…

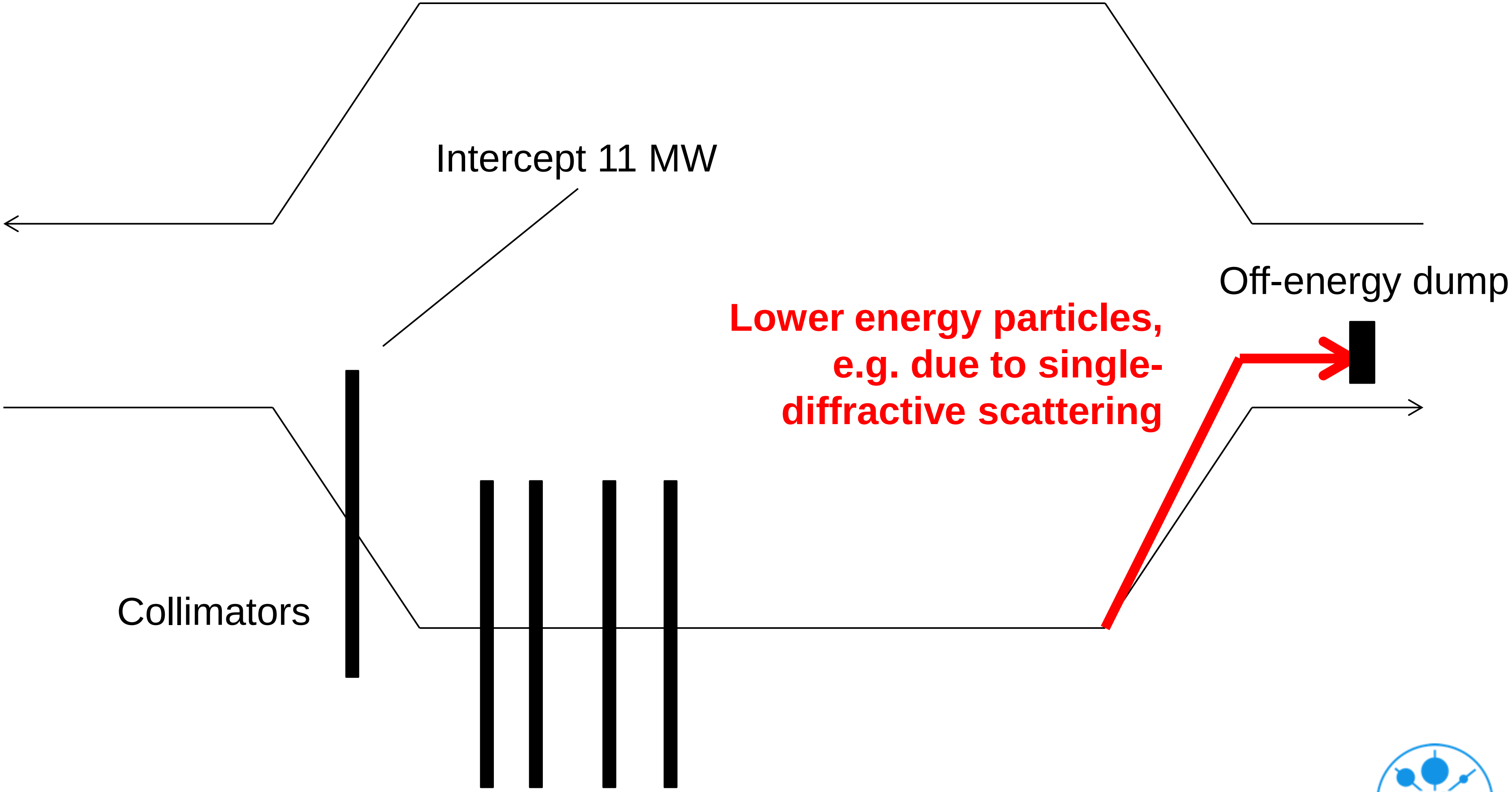
Towards an Optimal 50 TeV FCC Collimation System

- Will quickly show the a few concepts without details or any detailed study behind it…
  - Strong warm dogleg bending magnets and a wide tunnel
  - Combined betatron and momentum collimation system
  - Improved phase space coverage by additional primary collimators

1) Strong warm dogleg bending magnets and wide tunnel

- Background:
  - The two beam pipes in the SC magnets need to be reasonable close to each other.
  - Not enough space between the two pipes to collimate beam in a given pipe.
  - The distance between the beam pipes must be increased to allow collimation of one beam and not the other (separated vacuum systems).
- Consequence 1: Warm (or SC?) dogleg bends must separate the distance between the two beams by some amount.
- Consequence 2: The collimation regions needs an enlarged tunnel width.
- Solution: **Make the dogleg bends strong enough to separate and locally catch the single-diffractive scattering protons or ion debris (dispersion!).**
- Studied for LHC collimation but too late to restart civil engineering at the time (missed by 6 months).

The dog-leg solution for p and ions…



Intercept 11 MW

Off-energy dump

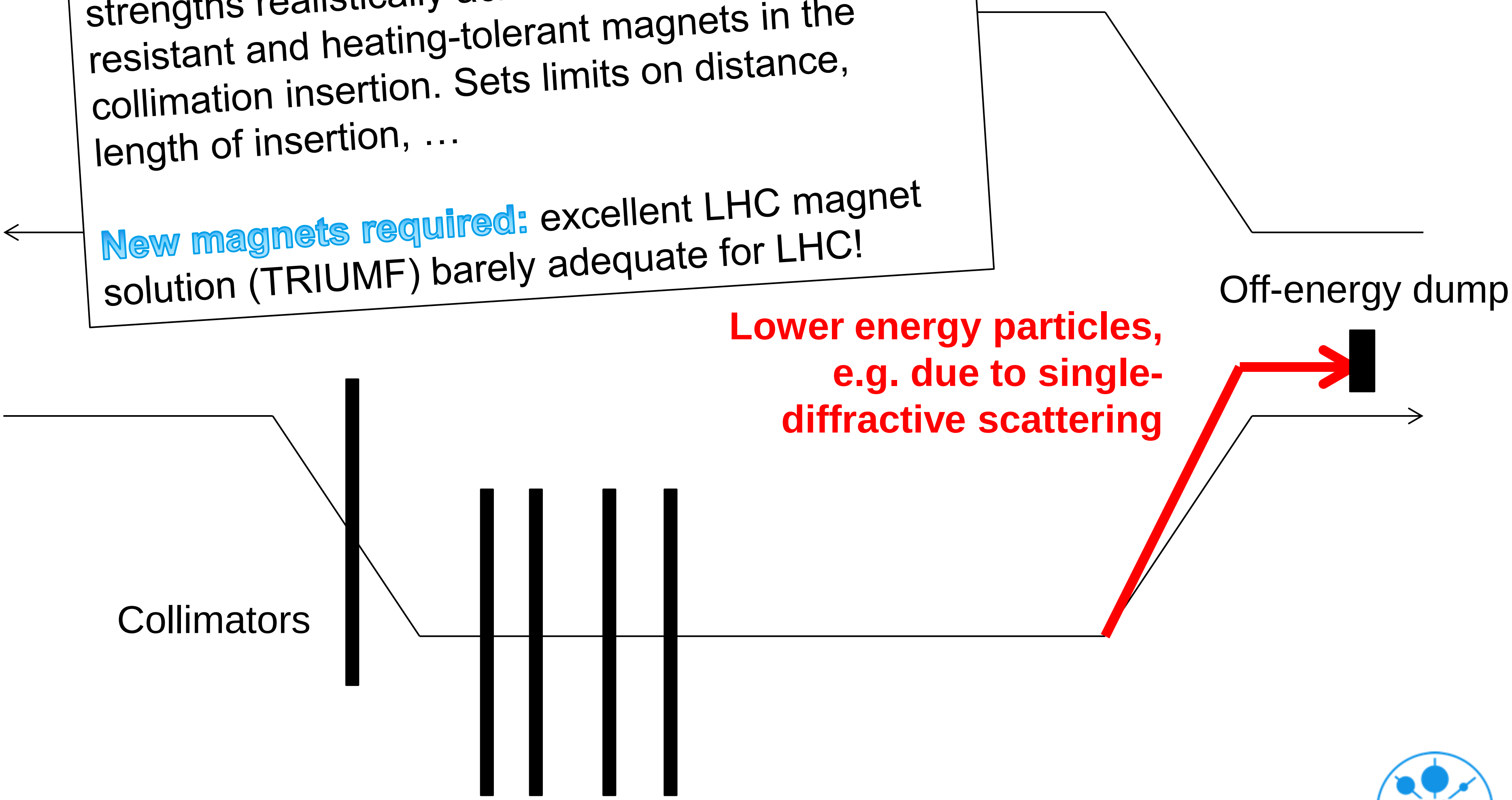
Lower energy particles, e.g. due to single-diffractive scattering

Collimators

The dog-leg solution for p and ions…

Critical engineering input: Maximum field strengths realistically achievable for the radiation-resistant and heating-tolerant magnets in the collimation insertion. Sets limits on distance, length of insertion, …

New magnets required: excellent LHC magnet solution (TRIUMF) barely adequate for LHC!

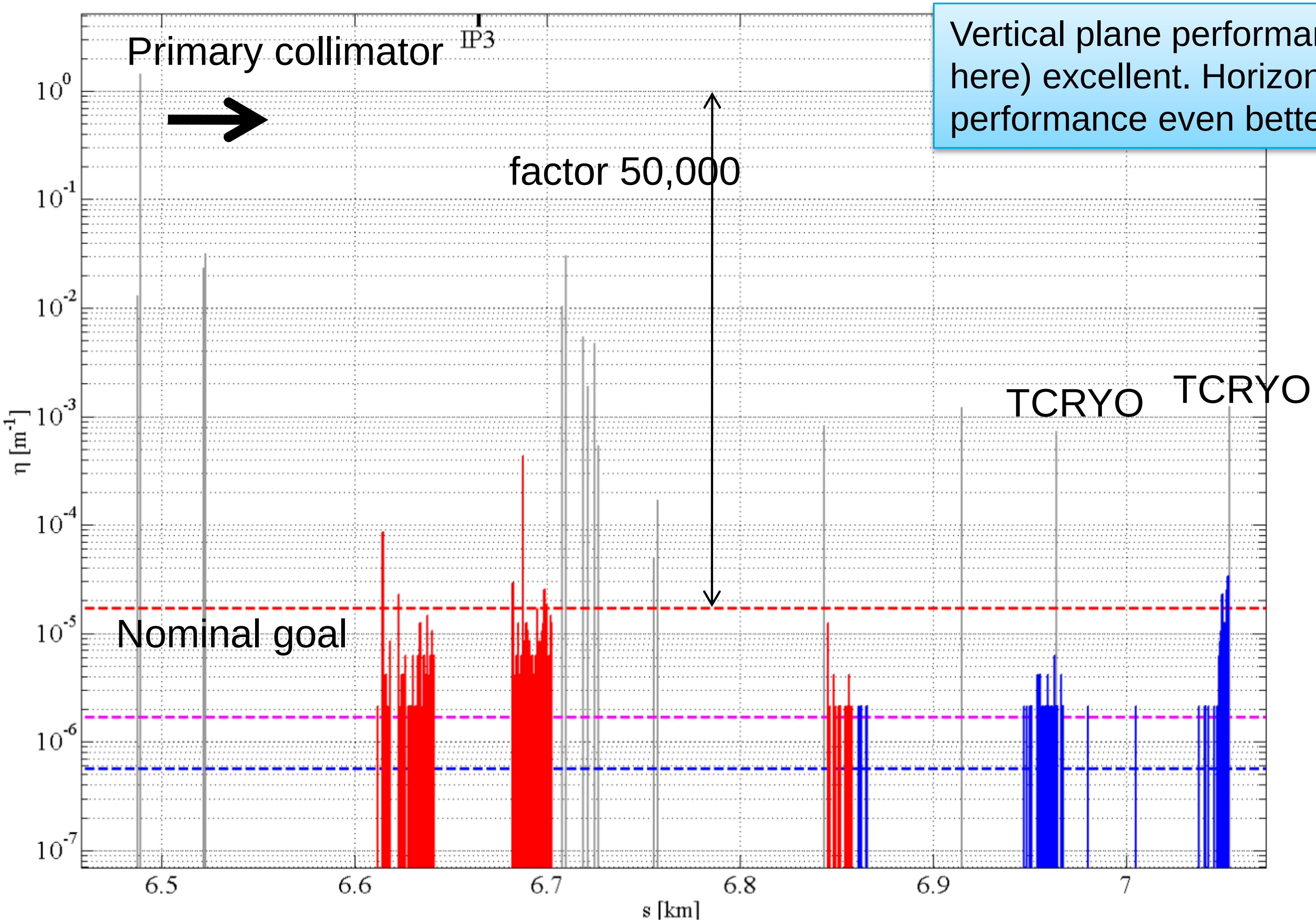


Lower energy particles, e.g. due to single-diffractive scattering

2) Combined Betatron and Momentum Cleaning

- One of the **strongest sources of off-momentum halo are the betatron collimators**.
- Systems can easily be combined, saving overall length, costs and improving performance.
- The **momentum collimation must, of course, be downstream of the betatron collimation system**.
- This **solves ion leakage problem**.
- Clever **combination with strong dog-leg magnets** reduces needs on number of collimators.
- We had a solution for LHC ready worked out…

LHC Combined Collimation System in IR3 plus two absorbers → Vertical Betatron Cleaning



Vertical plane performance (shown here) excellent. Horizontal plane performance even better!

Notes on Combined Betatron/Momentum Collimation

- The LHC momentum collimation was designed as a fully horizontal system.
- By placing 6 additional collimators at existing (non-optimized) locations, excellent performance was shown in simulations with such a combined system.
- Would have reduced the total number of LHC collimators by 28. **Therefore also reduced impedance**.
- Not done, because the LHC phase 1 collimation at 4 TeV good enough, so improvements not needed.
- Based on this, I believe that **an optimal FCC solution can be worked out with important gains and improvements.**

3) System with Better Operational Robustness

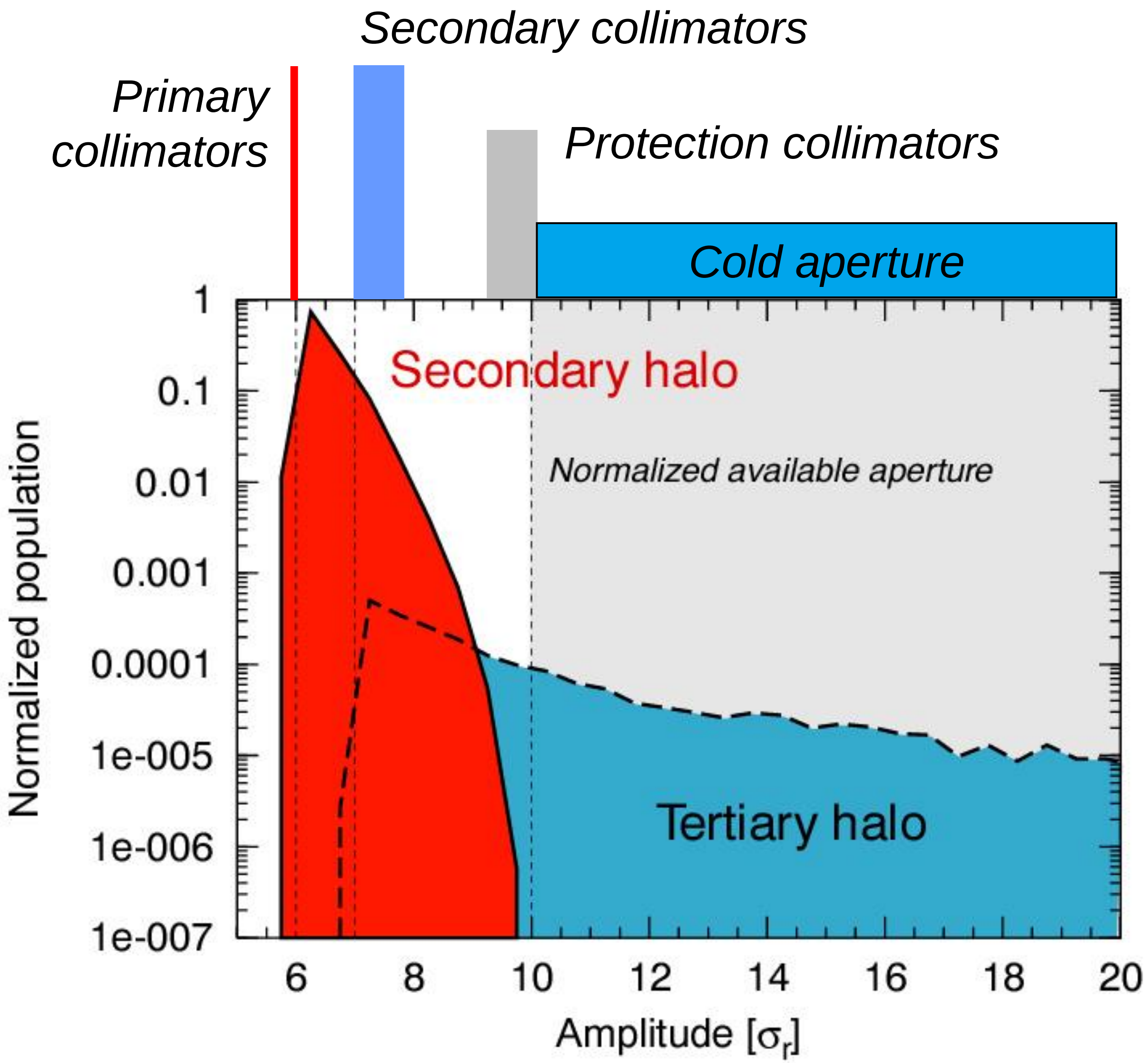
- The collimator aperture (a_{coll}) is a function of the triplet aperture ($a_{triplet}$) that must be protected, the beta functions and the extent of primary and secondary beam halos:

~ 0.6

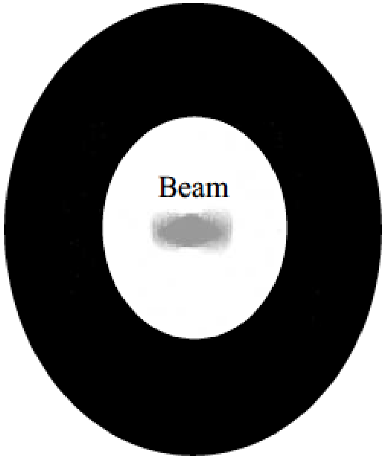
$$a_{coll} \le a_{triplet} \cdot \sqrt{\frac{\beta_{coll}}{\beta_{triplet}} \cdot \left(\frac{A_{primary}^{\max}}{A_{secondary}^{\max}} \right)}$$

- Best strategy: **as tight as possible gaps of the primary collimators**! Also allows operating in still quite linear phase space (non-linearities kill collimation hierarchy).
- Solve **impedance by transverse damper, secondary collimators at larger beta function, reduced total collimator length (fewer, shorter), combining systems, material, …**

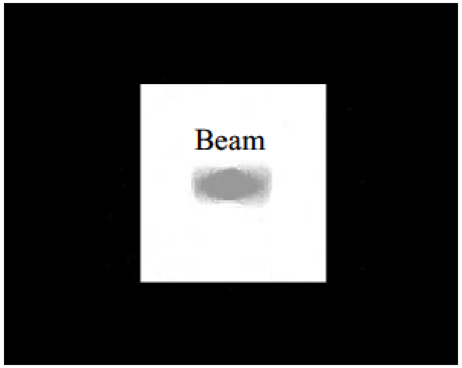
Reminder Hierarchy: Primary collimators at 6 σ



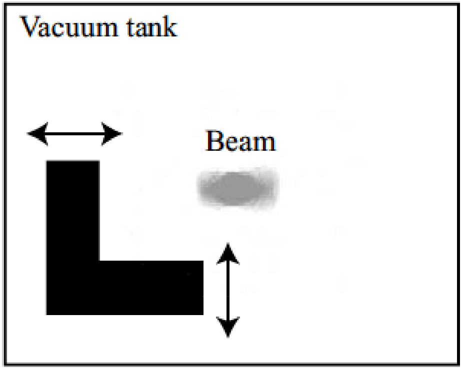
Two-Sided Collimators to Constrain Phase Space



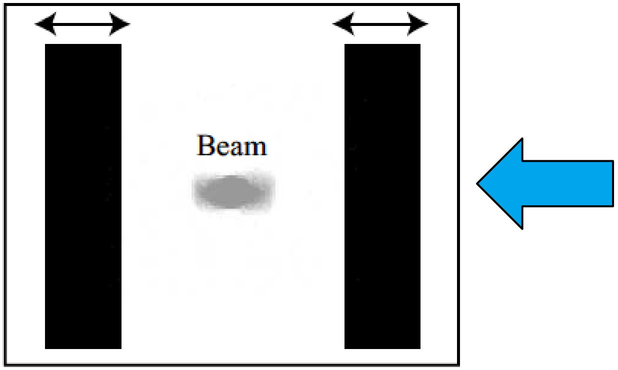
(a) Fixed elliptical mask



(b) Fixed rectangular mask



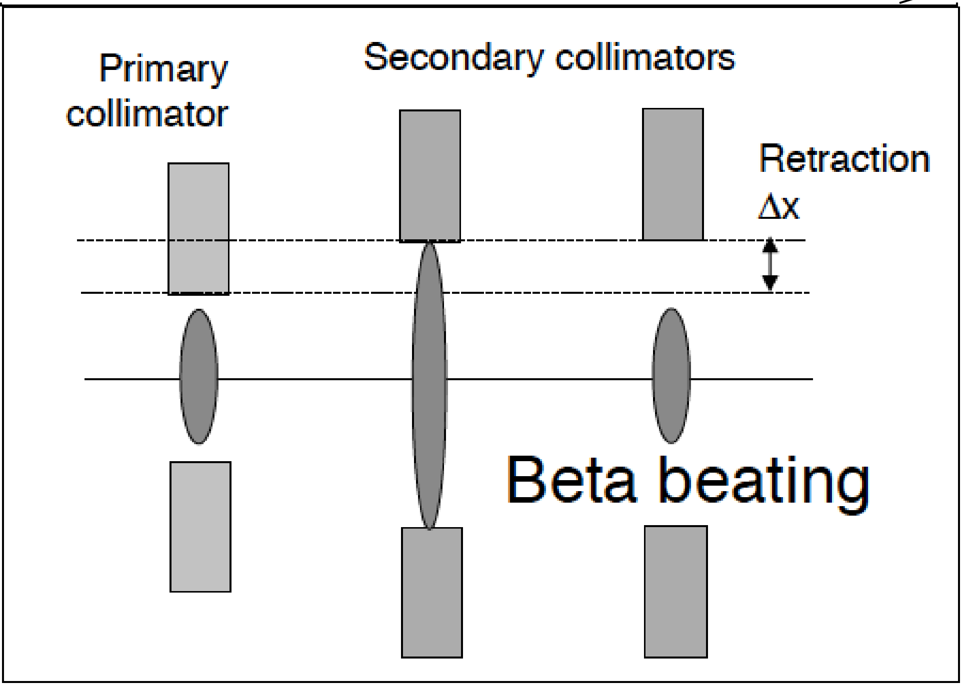
(c) One-sided, L-shaped movable jaw



(d) Two parallel movable jaws

Unavoidable Imperfections Eat Up Margins → Limit β*

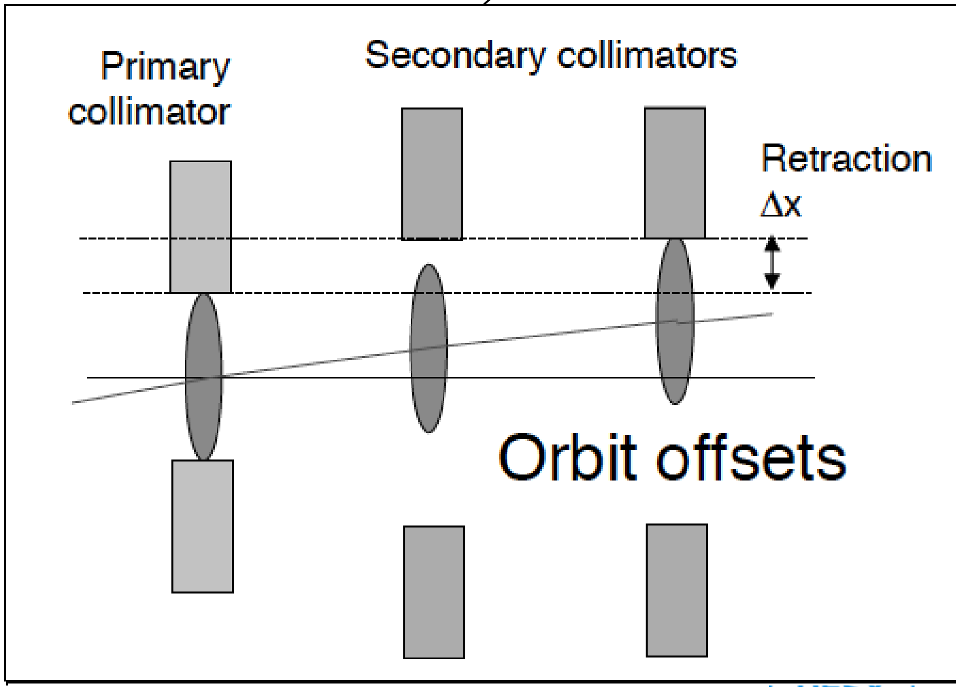
$$\beta^* \geq \frac{C^2}{a^2_{triplet} \cdot \beta_{coll}} \cdot \left(n_{\mathrm{prim}} + \Delta A_{\mathrm{max}} + 1.7 \cdot \left[n_{\mathrm{prim}} \cdot \sqrt{\frac{\Delta\beta_{\mathrm{max}}}{\beta_0}} + \frac{\Delta x^{\mathrm{max}}_{\mathrm{orbit}}}{\sigma_{\mathrm{x}}} \right] \right)^2$$


Primary collimator

Secondary collimators

Retraction Δx

Beta beating

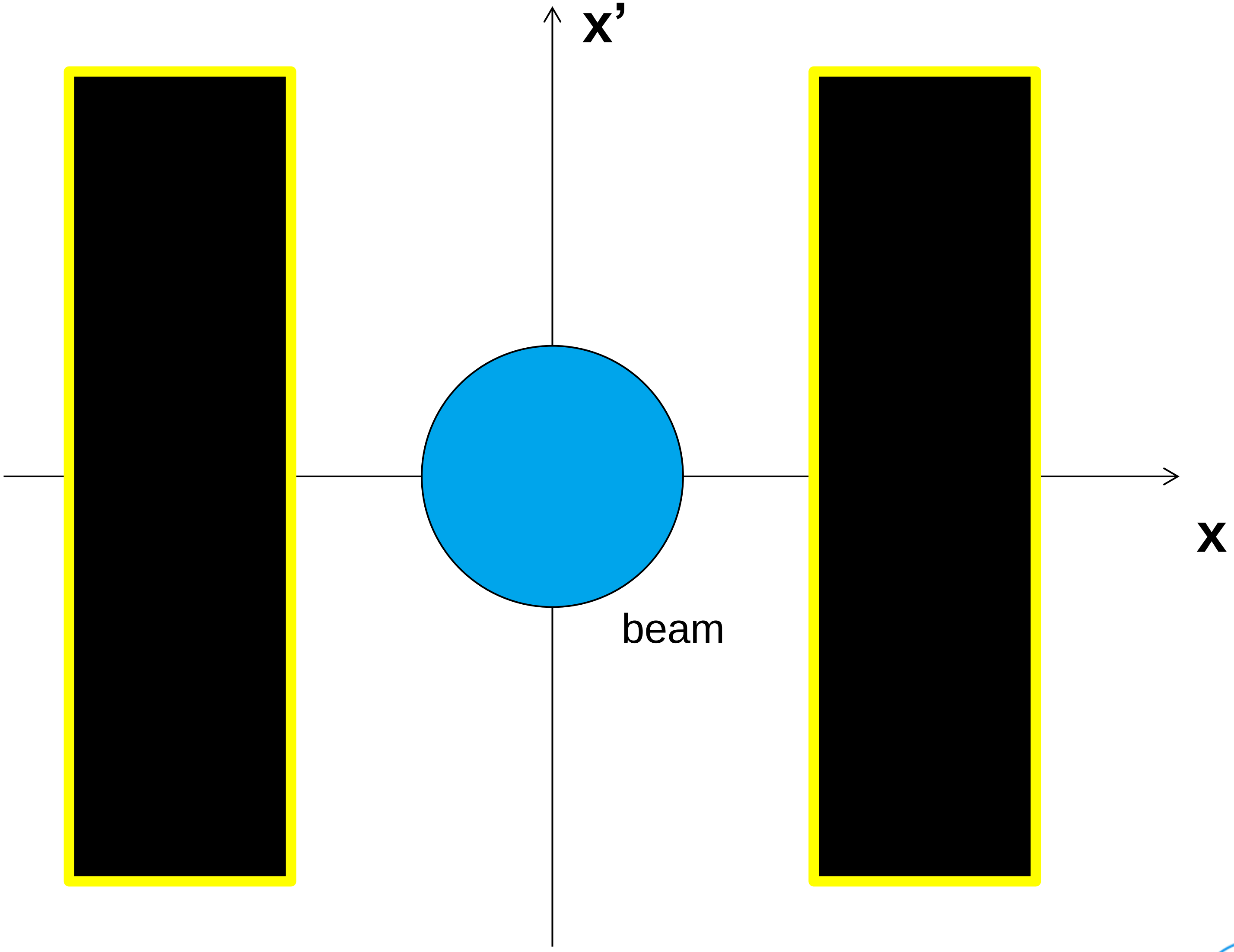

Primary collimator

Secondary collimators

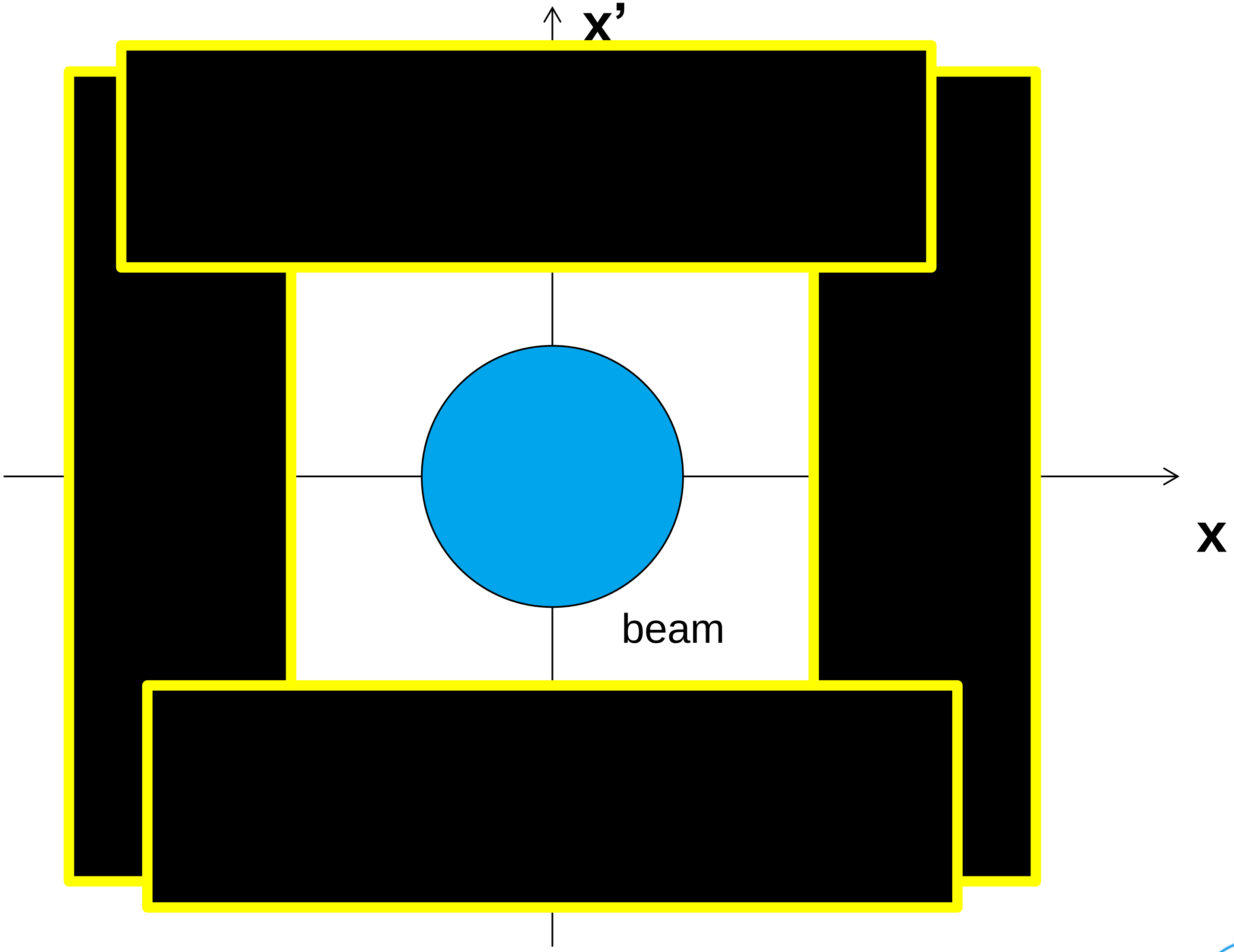
Retraction Δx

Orbit offsets

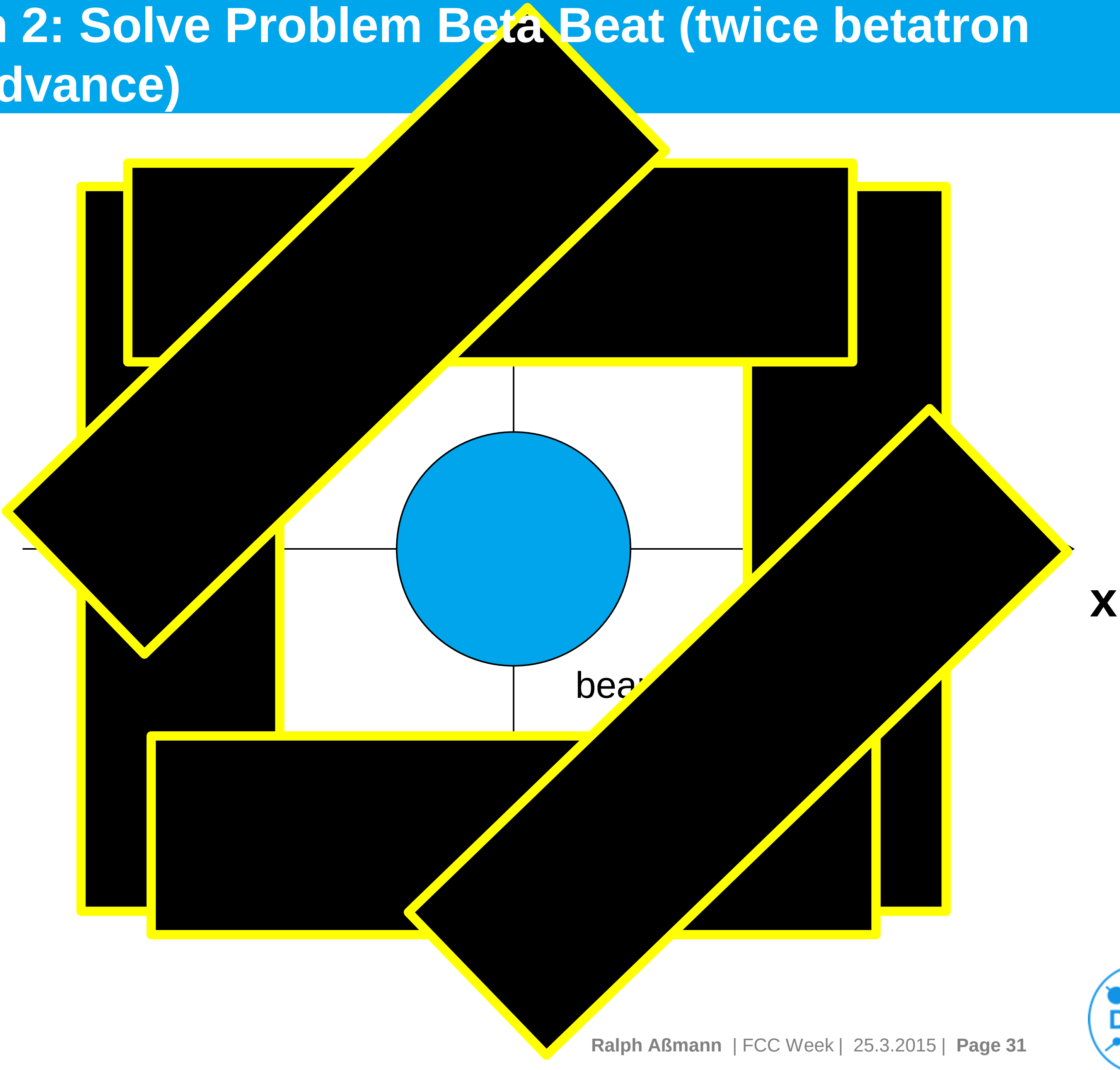
Solution: Better Phase Space Coverage by Primary Coll.



Solution 1: Solve Problem Free Orbit Oscillation



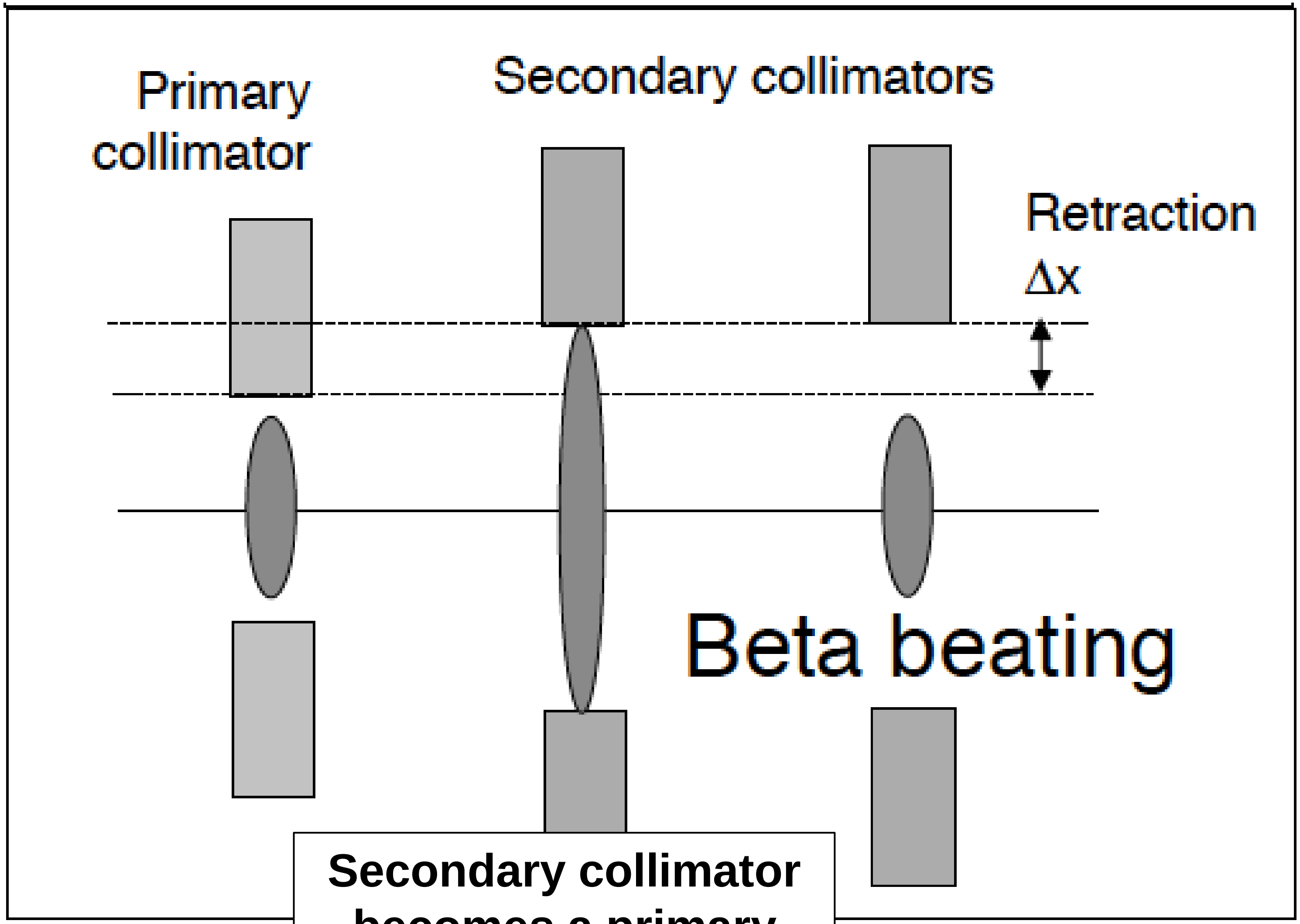
Solution 2: Solve Problem Beta Beat (twice betatron phase advance)



Triple Primary Collimation – What Does it Mean?

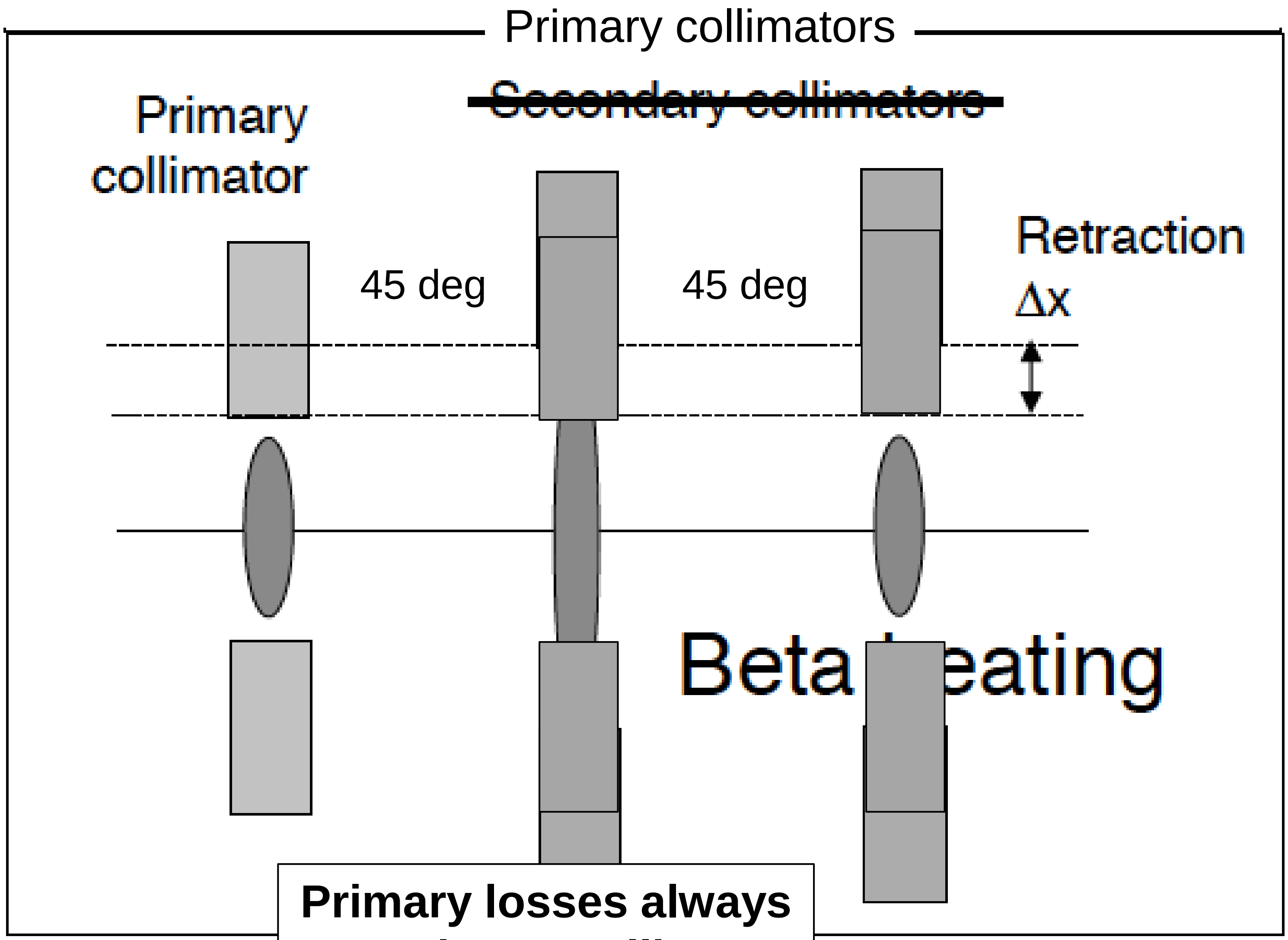
- This solution will have **three primary betatron collimators per plane, separated by 45 degree** (instead of one in the present system).
- This is **robust against free betatron orbit perturbations and transient beta beat errors**.
- Being robust about operational errors, it also offers **better machine protection**.
- This approach has much better operational stability. Stability can be used to go to **smaller beta* and higher luminosity**, while staying very safe.
- It is the **logical next step beyond LHC**. For LHC I looked at it (with Verena Kain) but we could not do it due to insufficient phase advance in the fixed collimation insertions in the LHC.

Beta Beat Impact: Single Primary Collimation



Secondary collimator becomes a primary collimator

Beta Beat Impact: Triple Primary Collimation



Primary losses always at a primary collimator

Triple Primary Collimation – Is it really a good idea?

- Does it **violate the two-stage theory**?

  Yes, but the **present LHC system is already way beyond this theory**: three planes, four stages, reduced number secondary collimators, non-optimal phase advance.

  Remember: **Two-stage theory** defines collimators for an optimal system in one plane only and for only two stages! **Not good enough for TeV hadron colliders, even though an excellent starting point.**

- But this **adds even more collimators and the impedance will stop us**, so we will loose!?

  No, not necessarily. The later primary collimators already work also as secondary collimators. One could then reduce number of sec. coll.

  Also, it is the **total length that matters**. If needed, the length of one collimator can be distributed to three shorter collimators, while restricting the phase space!

Outlook

- Unavoidable beam losses in the FCC will generate **serious power loads on collimators (10 MW)**. This is difficult.
- The **higher beam energy is bad for collimation efficiency** due to laws of physics in particle-matter interaction (it is harder to stop more energetic particles).
- LHC collimation was addressed seriously very late. we had to work hard and accept many compromises to work out last minute solutions.
- For FCC a serious effort will be required and also **innovative solutions** should be pursued in order to reach goals.
- As the FCC **defines the ring from scratch there is quite some opportunity for a much improved collimation system**.
- I would go to new magnet designs, strong dogleg bends, combined system functions with reduced number of collimators and a tighter phase space coverage (“triple primary collimation” TPC system).