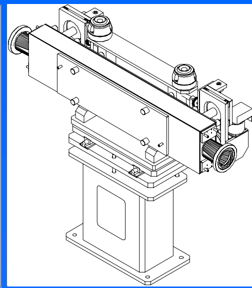
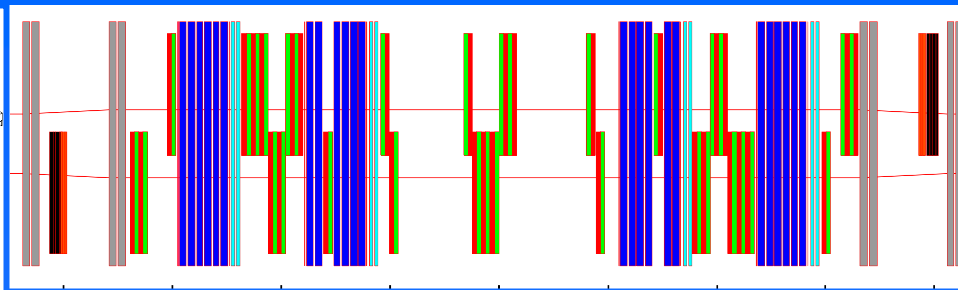
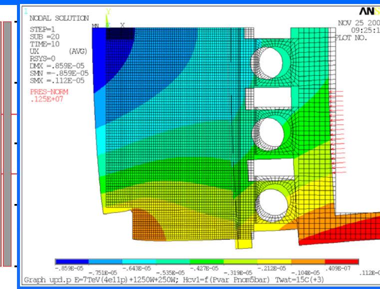
LHC Collimation Project CERN







Choices for the Collimation System & Collimation Impedance Issues

R. Assmann

For the collimation team

Outline

- The collimation project and team
- Reminder: Requirements and design goals
- **Choice 1a:** The phased approach
- **Choice 1b:** Material and length of jaws for phase 1
- **Choice 2:** Conceptual collimator design for phase 1
- **Choice 3:** Layout of cleaning insertions, in particular IR7
  - **Efficiency**
  - **Impedance**
- Future choices: Absorbers, shielding, motorization & local control, …
- Summary and outlook

The Collimation Team

Work and results:

O. Aberle, I.L. Ajguirei, R. Assmann, I. Baishev, A. Bertarelli, H. Braun, M. Brugger, L. Bruno, H. Burkhardt, E. Chiaveri, B. Dehning, A. Ferrari, B. Goddard, B. Holzer, J.B. Jeanneret, M. Jimenez, V. Kain, D. Kaltchev, I. Kouroutchkine, M. Lamont, M. Mayer, E. Metral, R. Perret, T. Risselada, J.P. Riunaud, S. Roesler, F. Ruggiero, R. Schmidt, D. Schulte, P. Sievers, H. Tsuitsui, V. Vlachoudis, L. Vos, E. Vossenberg, J. Wenninger

35 people contributing 7 FTE (2003) ➔ 13 FTE (2004)

➔ Not a complete summary of all the work…

Advice and link persons:

O. Bruning, P. Bryant, V. Mertens, R. Ostojic, C. Rathjen, F. Schmidt, J. Uythoven, W. Weterings, T. Wijnands, F. Zimmermann

Reminder: Requirements & Design Goals

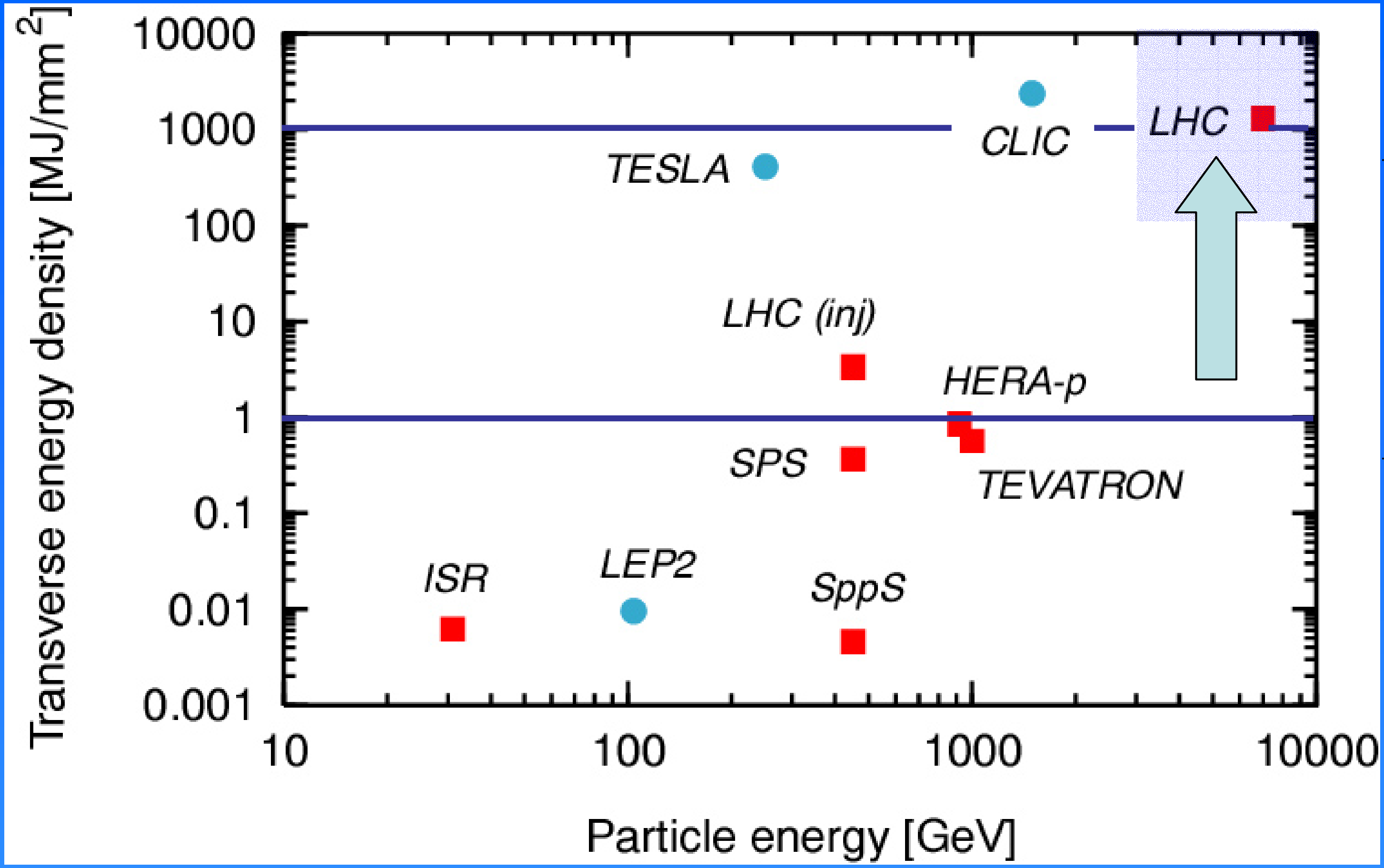
- **Efficient cleaning of the beam halo** during the full LHC beam cycle (avoid beam-induced quenches of the SC magnets in routine operation).
- **Minimization of halo-induced backgrounds** in the particle physics experiments.
- **Passive protection** of the machine aperture against irregular beam (beam loss monitors at the collimators detect abnormally high loss rates ➔ beam abort trigger). With MPWG.
- **Scraping** of beam tails and diagnostics of halo population.
- **Abort gap cleaning** in order to avoid spurious quenches after regular beam dumps.

To achieve this important challenges must be met!

Some Numbers

• High stored beam energy (melt 500 kg Cu, required for 10^{34} cm^{-2} s^{-1} luminosity)	**~ 350 MJ/beam**
• Small spot sizes at high energy (small 7 TeV emittance, no large beta in restricted space)	**200 μm (at coll.)**
• Large transverse energy density (beam is destructive, 3 orders beyond Tevatron/HERA)	**1 GJ/mm^2**
• High required cleaning efficiency (clean lost protons to avoid SC magnet quenches)	**99.998 % (~ 10^{-5})**
• Collimation close to beam (available mechanical aperture is at ~10 σ)	**6-7 σ**
• Small collimator gap (impedance problem, tight tolerances: ~ 10 μm)	**~ 3 mm (at 7 TeV)**
• Activation of collimation insertions (good reliability required, very restricted access)	**~ 1-15 mSv/h**
• Big system	**IR3, IR7, other locations**

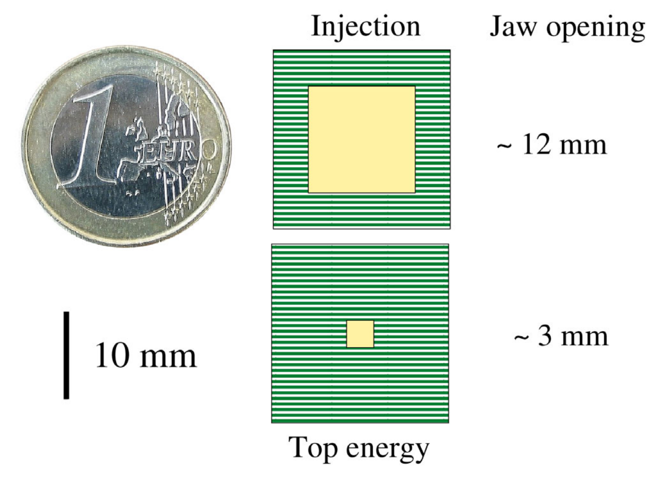
(nominal design parameters)



At less than 1% of nominal intensity LHC enters new territory (damage, quench, …)!

There is no easy start-up for collimation!

Gaps are small and impedance is high!



Reminder on required inefficiency:

(Intensity at the quench limit)

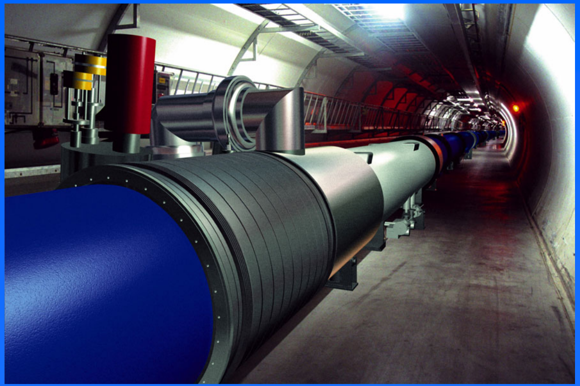


Illustration of LHC dipole in tunnel

Allowed intensity

Quench threshold (7.6 ×10⁶ p/m/s @ 7 TeV)

$$N_p^{\max} \approx \tau \cdot R_q \cdot L_{dil} / \eta_c$$

Beam lifetime (e.g. 0.2 h minimum)

Dilution length (50 m)

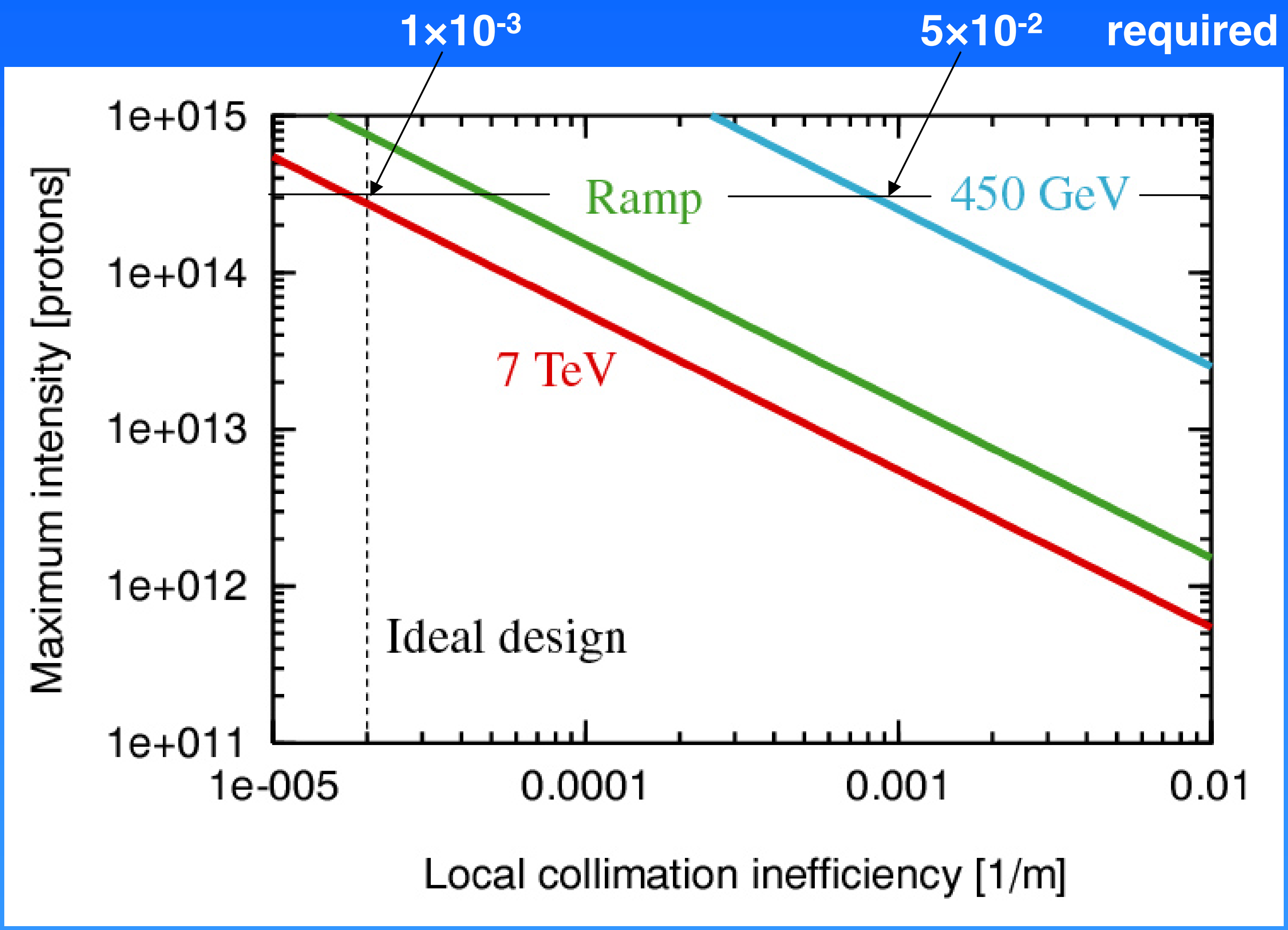
Cleaning inefficiency

=

$$\frac{\text{Number of escaping p } (>10\sigma)}{\text{Number of impacting p } (6\sigma)}$$

Collimation performance can limit the intensity and therefore LHC luminosity.

Design Goal for Cleaning Inefficiency



(assuming 50m dilution length)

For a 0.2 h minimum beam lifetime during the cycle.

Dilution length is under study (V. Kain, B. Holzer, R. Assmann, …).

Challenges for LHC Collimation

SOLUTION?

- Good robustness
- High efficiency
- Low impedance
- Low activation
- Reasonable cost
  Fast schedule
- Reasonable tolerances

Choice 1a: The Phased Approach

Tradeoffs:

Good robustness (carbon)	←→	Low impedance (metal)
High efficiency (good absorption)	←→	Good robustness (bad absorption)
Low impedance (short jaws)	←→	High efficiency (long jaws)

1. **Conflicting requirements.**
2. **Advancing state-of-the-art by 2-3 orders of magnitude.**

→ **No unique solution for everything** (injection, ramp, collision, …)

Various **sub-systems with dedicated usages**, targeted at specific requirements (e.g. maximum robustness at injection/ramp, minimum impedance at collision).

Staged approach for minimum initial investment, minimum number of components, assuring to be ready in time. Possibility of upgrades.

The collimation phases

1) **Maximum robustness, minimum cost IR3/IR7 collimation system** (C) for injection&ramping, commissioning, early physics (running at impedance limit). Thin metallic coating for going further (survival of coating unclear).
2) **"Tertiary" collimators in IR1, IR2, IR5, IR7** for local protection and cleaning at the triplets. Movable, Cu, 1-1.5m long, at ~D1.
3) Thin targets for **beam scraping**.

→ Phase 1

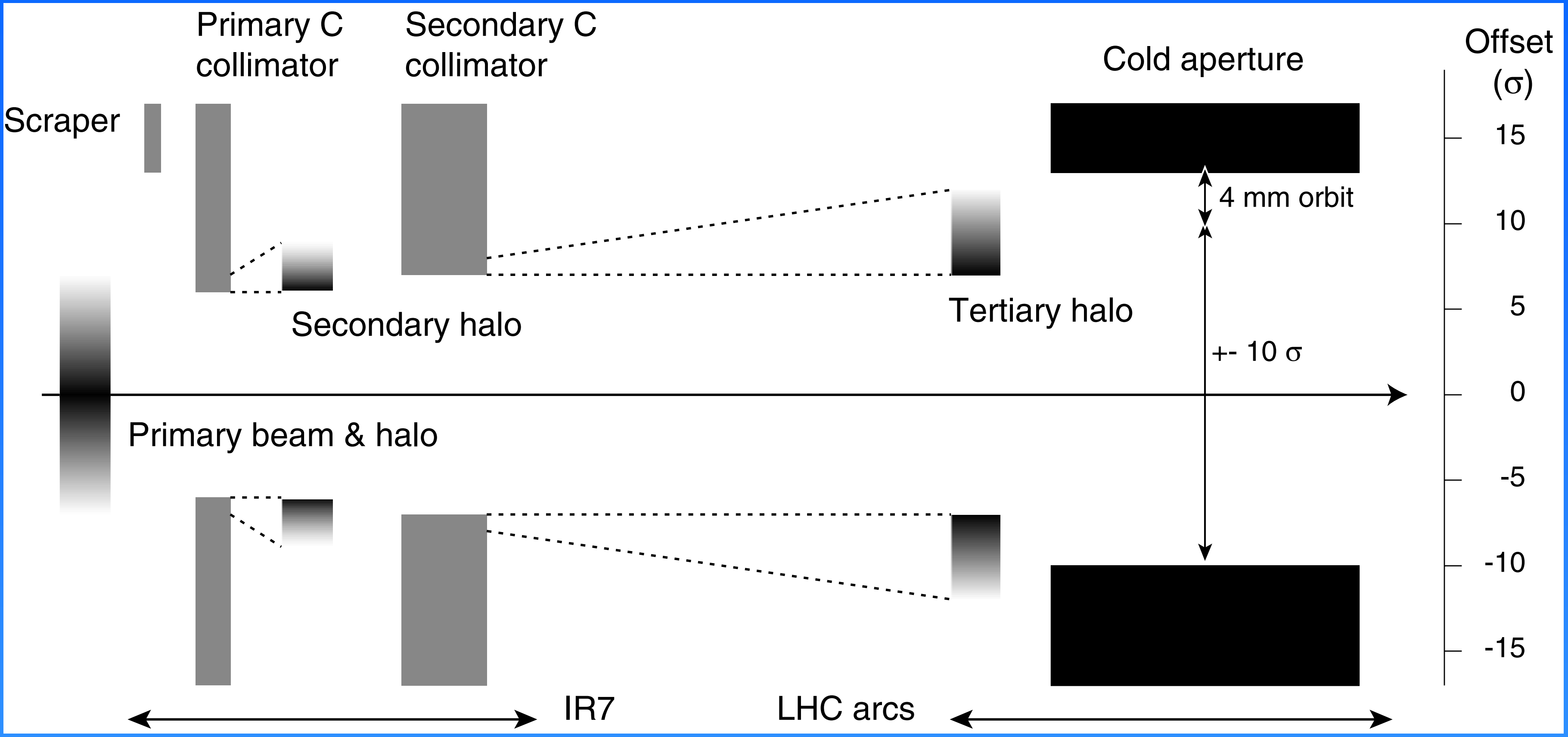
4) **Metallic "hybrid" secondary collimators** for nominal performance, used only at end of squeeze and stable physics.

→ Phase 2

5) **Additional placeholders** for upgrading to maximum cleaning efficiency.

→ Phase 4

Phase 1: Robust 2-stage system for injection/ramp



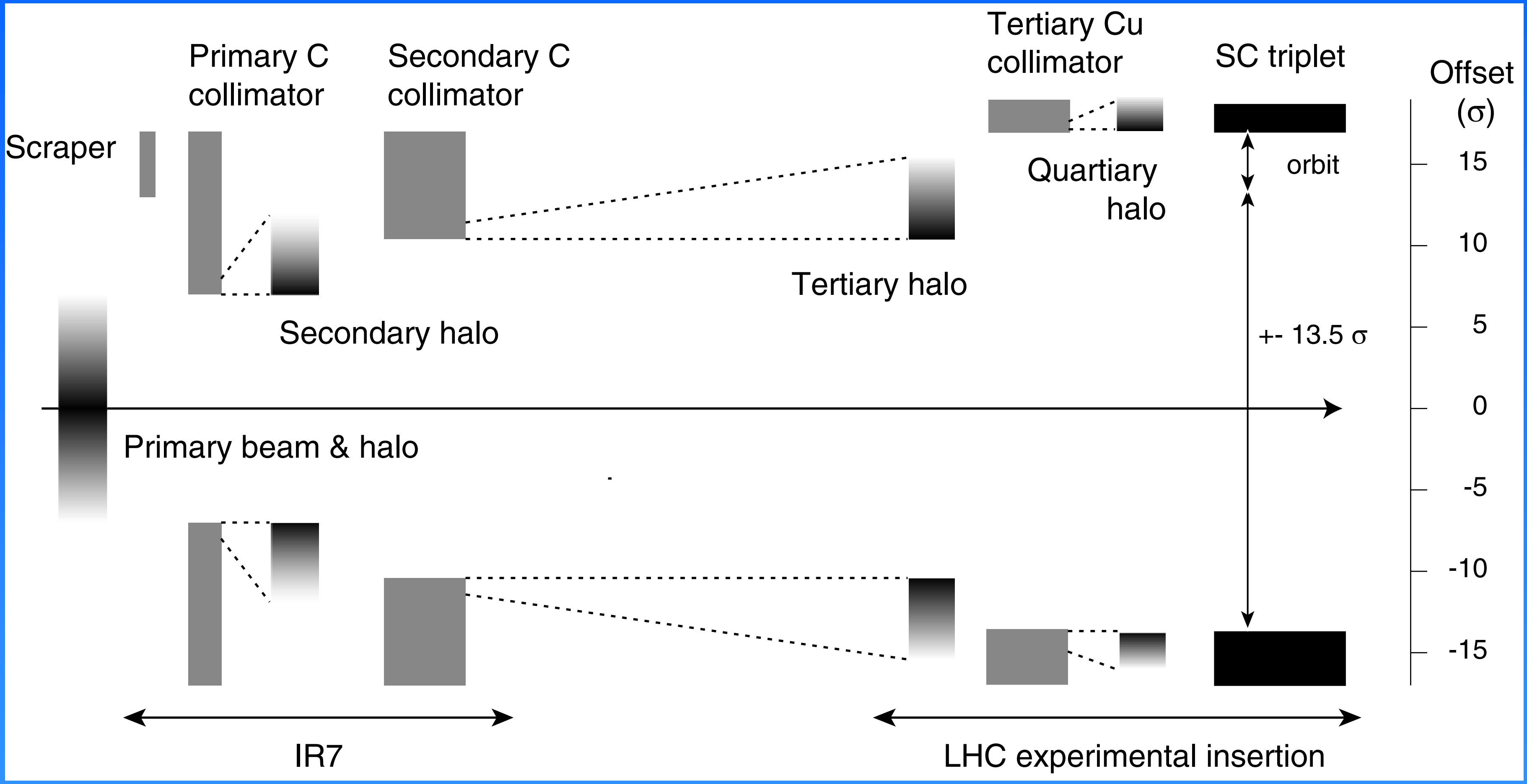
Primary/secondary collimators: Carbon-based.

Maximum robustness (withstand all expected beam impact at LHC).

Space allocations for phase 2 upgrade.

Injection scheme (6/7σ) to nominal/ultimate performance.

Phase 1: Used for early physics as a 3-stage system

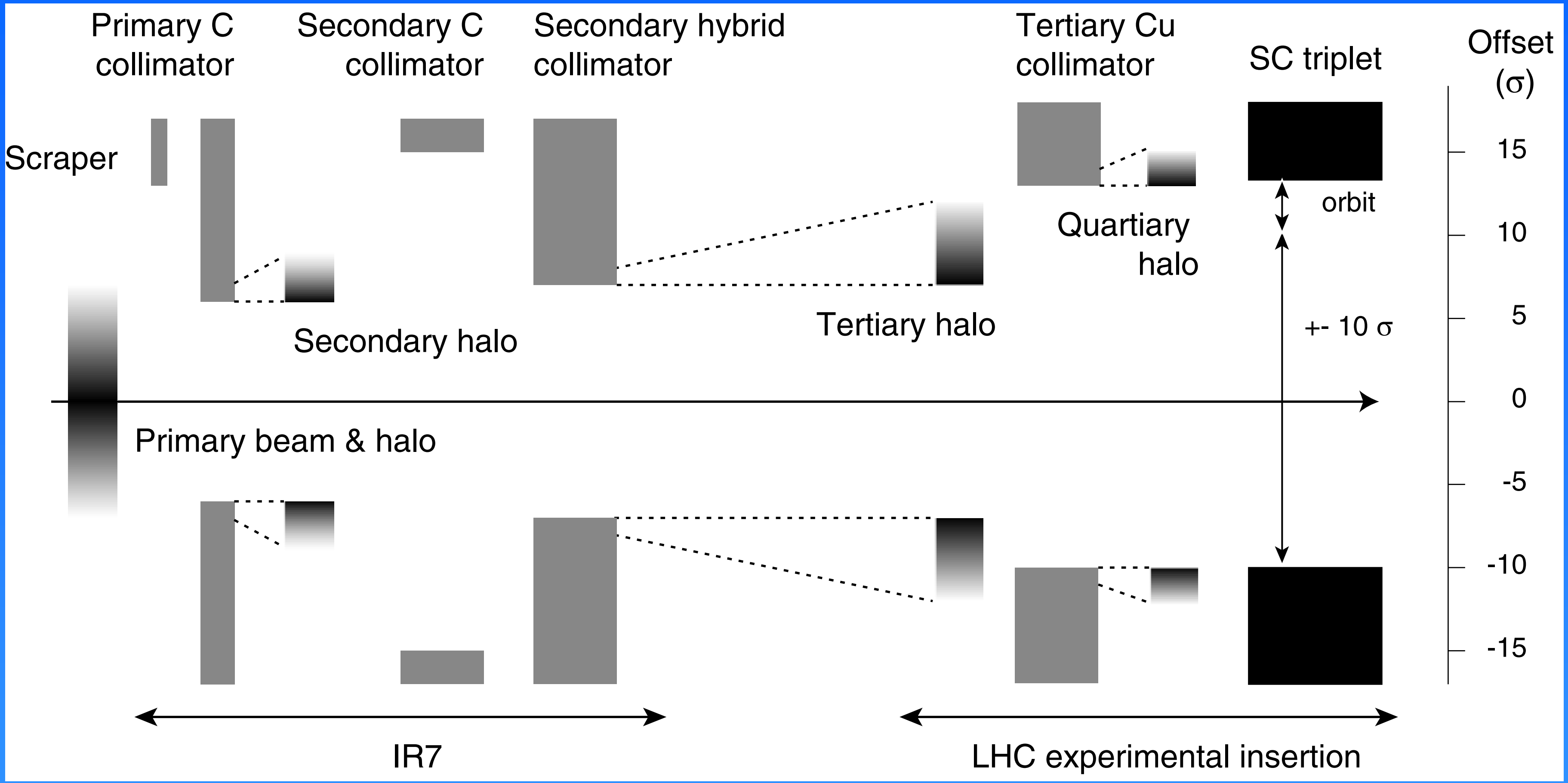


Phase 1 (early physics): **Operating at impedance limit with high robustness**.

Relaxed tolerances: mechanical and for orbit/beta beat, good efficiency.

Triplet protection and local cleaning at triplets.

Phase 2: Used for nominal physics



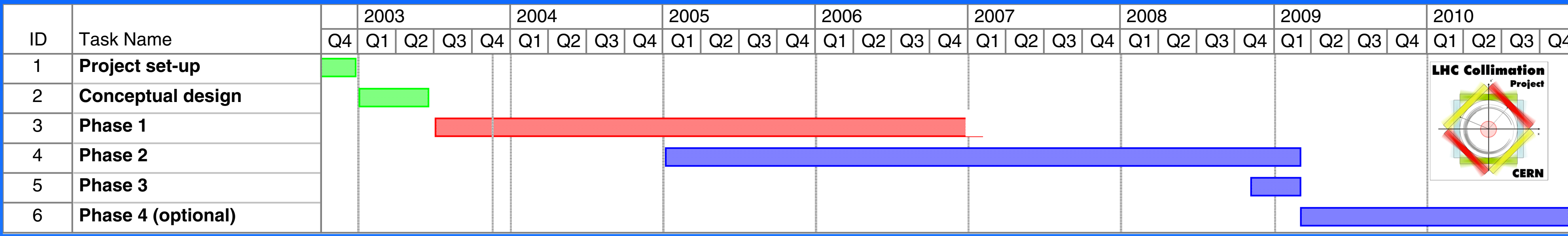
Secondary collimators: **C collimators (phase 1) not any more used for collision.**

Complemented by **sec. low impedance collimators** (sensitive).

Nominal (ultimate?) luminosity is achieved (6/7σ).

Timeline for collimation phases

(without commissioning of the system – included in project mandate)



Timeline for phase 1 is on the critical path since start of the project: design, prototyping, production, installation of a big and challenging system in 4 years.

Phase 1 is being realized…

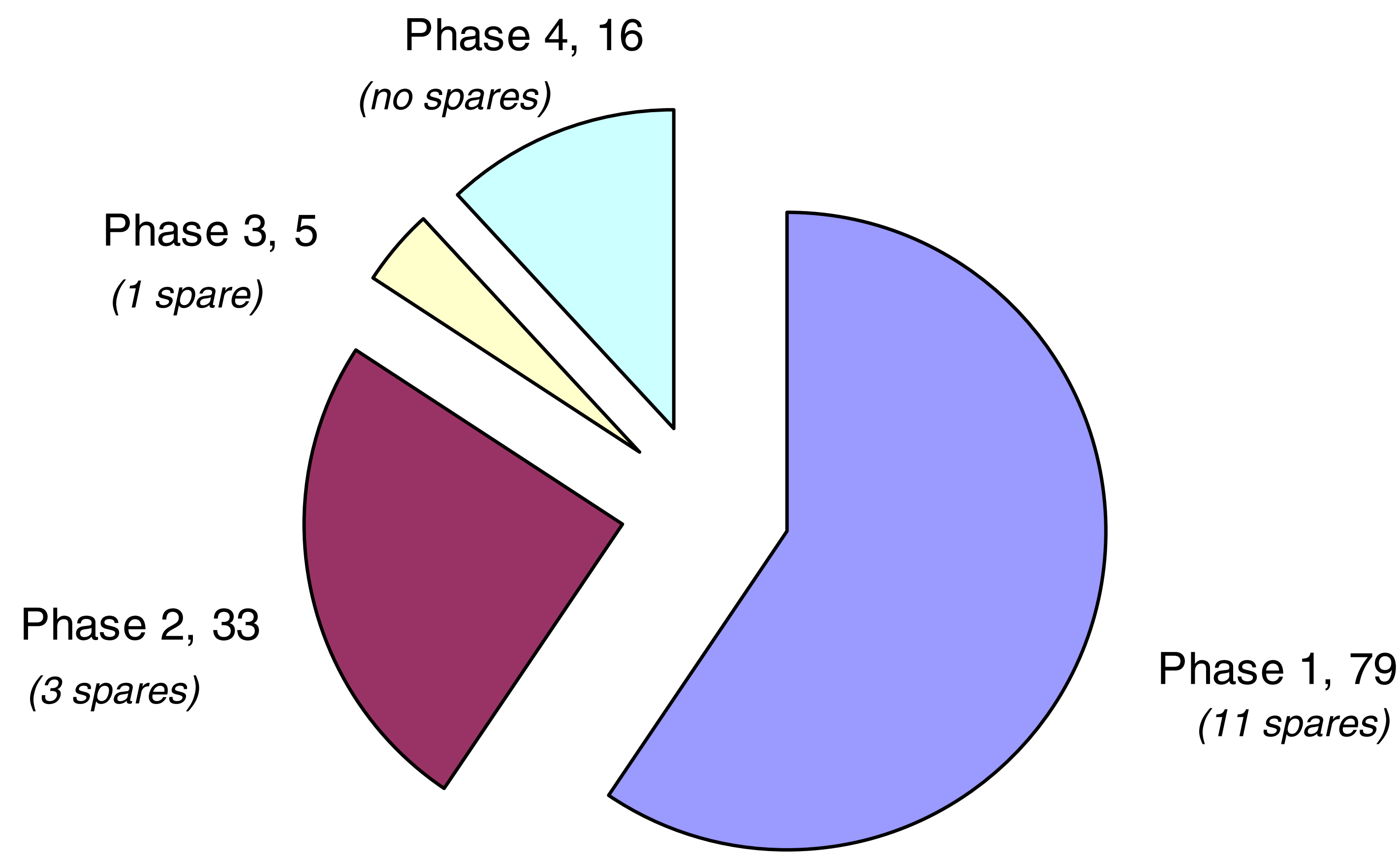
- with a collimator concept as **robust** as possible and as **simple** as possible
- relying as much as possible on available **experience**
- completed as **fast** as possible
- for a quite **low price**
- with **50 × better efficiency** than required at other machines (tighter tolerances)

Phased approach gives us **room for learning and developing the LHC collimation**.

Timeline for different phases extends until **2010/11**.

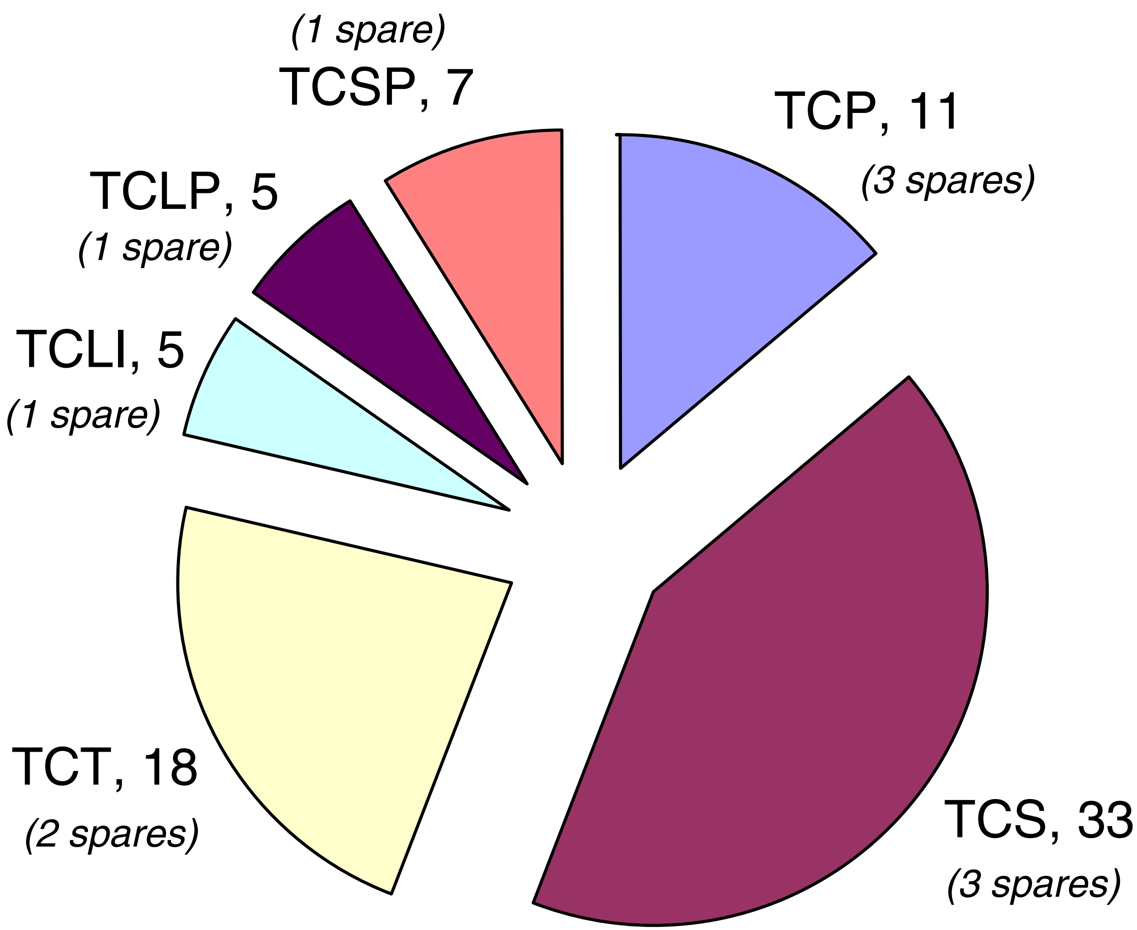
Start phase 2 design early to allow for nominal performance with advanced design (wait until phase is in series production)!

Phasing of ring collimators (including spares)



Ultimate efficiency: With **optional "Phase 4"** (not required for nominal – to be confirmed for new optics).

Collimators for Phase 1 (including spares)



Phase 1 is a big system:

- Total 79 components (95 in worst unlikely case).
- Much work overhead: 6 different types, not counting different azimuthal orientations for TCS!

TCP	*Primary collimator*
TCS	*Secondary collimator*
TCT	*Tertiary collimator*
TCSP	*Scraper*
TCLI	*Injection protection*
TCLP	*Physics protection*

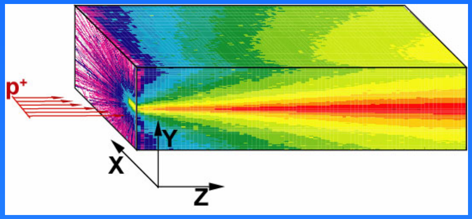
Concentrating on design of secondary collimators (TCS):

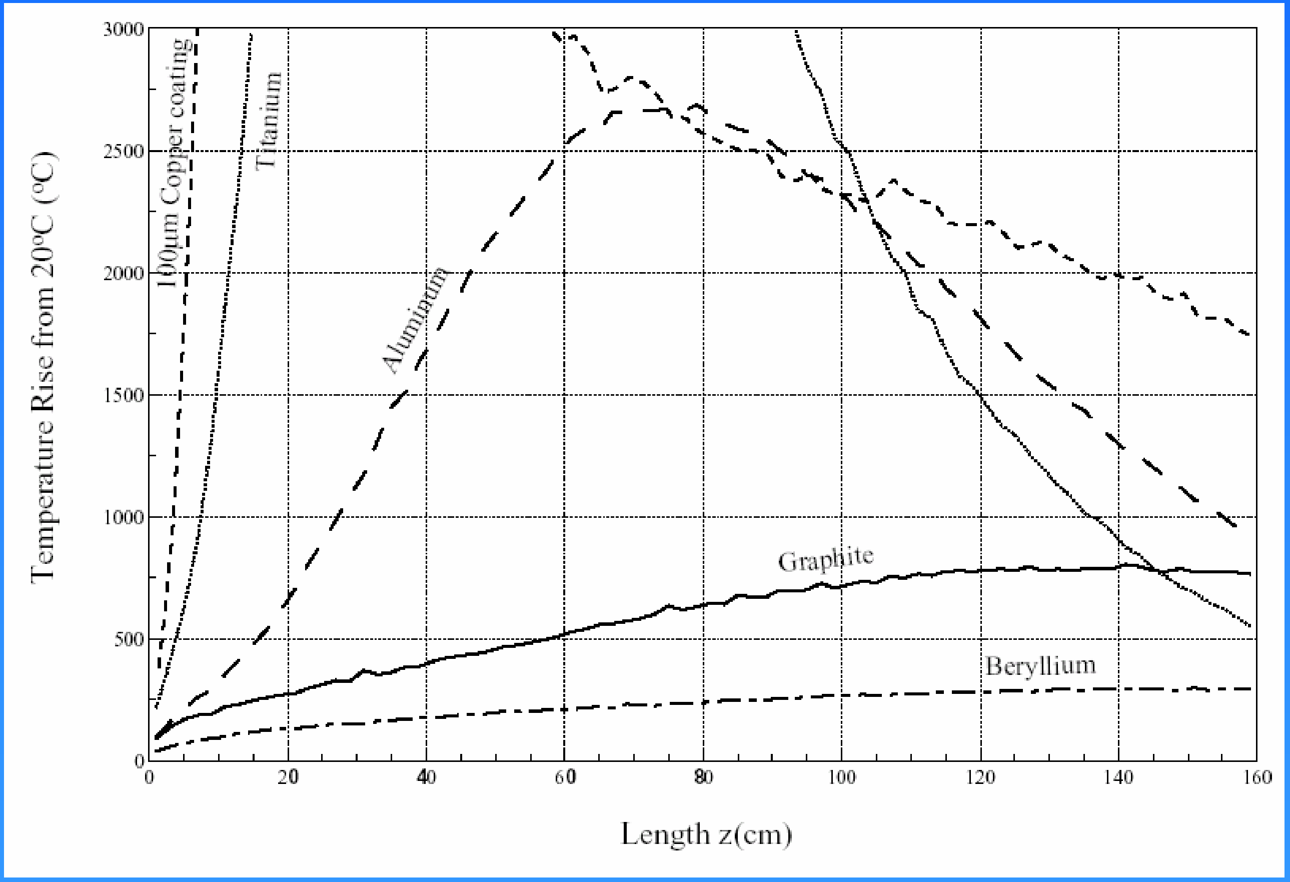
➔ most components and most difficult!

TCS design will serve as basis for TCP, TCSP, TCLP, and TCLI designs!

Choice 1b: Material and Length of Jaws

Design is driven by several irregular conditions:
➔Injection errors ➔ Asynchronous beam dumps ➔ Single module pre-fire
Analyzed with beam tracking, FLUKA and ANSYS.





Only low Z considered after FLUKA study!

A. Ferrari, V. Vlachoudis

Mechanical Stresses from ANSYS

(a) Injection

Material	Jaw length [cm]	Max. temperature [°C]	Stress σ_{equiv} [MPa]	σ_{allow} [MPa]	Suitability
Carbon-Carbon	20	335	4.4	86	yes
	100	345	12.7	86	yes
Graphite	20	335	3.1	18	yes
	100	345	6.2	18	yes
Beryllium	20	168	334	160	no
	100	200	440	160	no

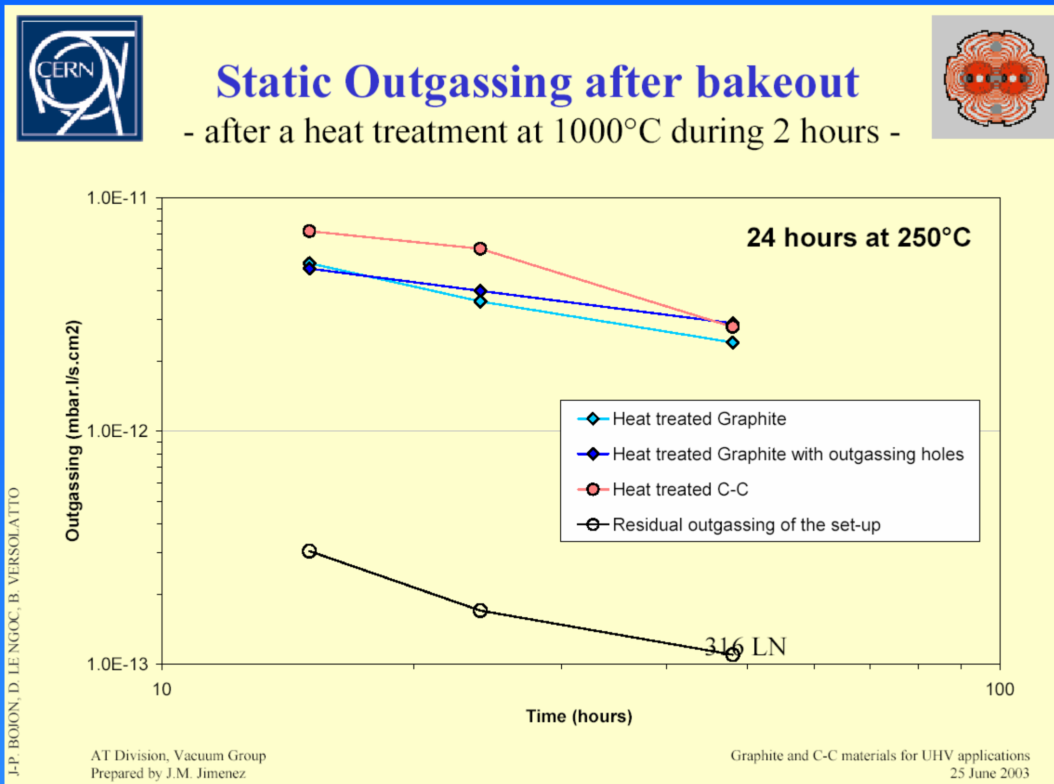
(b) 7 TeV

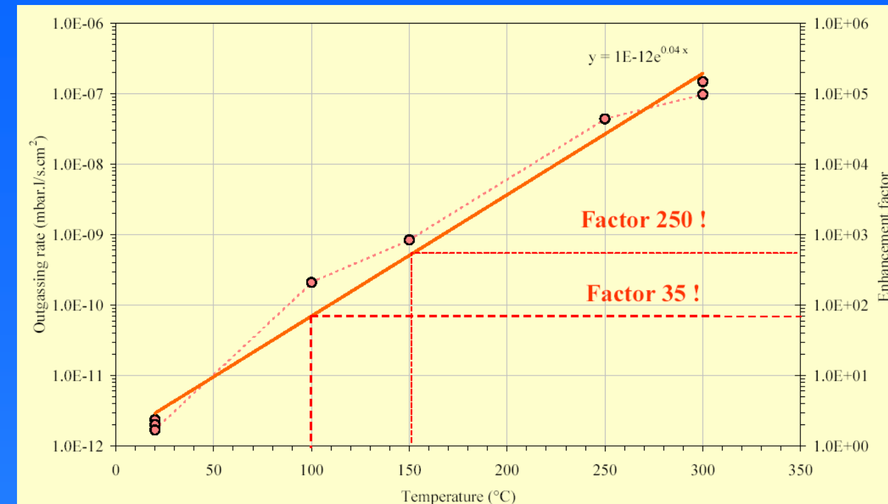
Material	Jaw length [cm]	Max. temperature [°C]	Stress σ_{equiv} [MPa]	σ_{allow} [MPa]	Suitability
Carbon-Carbon	20	212	20.8	86	yes
	100	551	82.0	86	yes
Graphite	20	212	4.4	18	yes
	100	551	17.8	18	yes
Beryllium	20	116	584	160	no
	100	168	1248	160	no

O. Aberle, L. Bruno

Only graphite or carbon-carbon found to fulfill robustness requirements!

Compatibility with LHC UHV





J-P. BOJON, J.M. JIMENEZ,
D. LE NGOC, B. VERSOLATTO

Conclusion: **Graphite-based jaws are compatible** with the LHC vacuum.

The outgassing rates of the C jaws will be optimized by **material and heat treatment under vacuum, an in-situ bake-out and a proper shape design**.

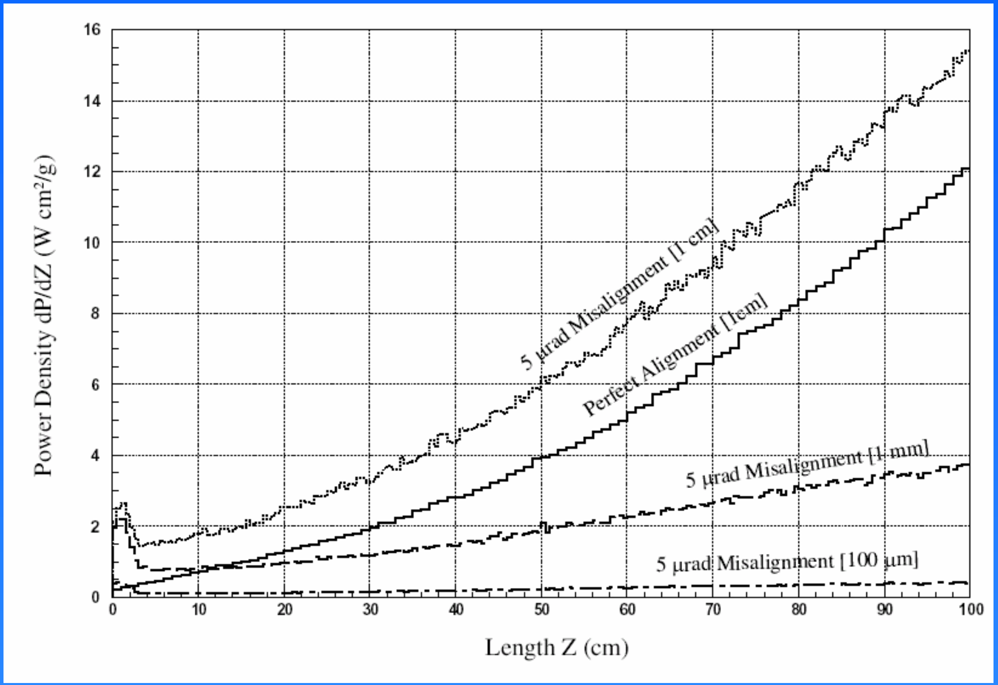
No indication that **graphite dust** may be a problem for the LHC.

The magnitude of a **local electron cloud** and its possible effects are studied.

Heat Load on Collimators

Mode	T [s]	τ [h]	R_{loss} [p/s]	P_{loss} [kW]
Injection	cont	1.0	0.8×10^{11}	6
	10	0.1	8.6×10^{11}	63
Ramp	≈ 1	0.006	1.6×10^{13}	1200
Top energy	cont	1.0	0.8×10^{11}	97
	10	0.2	4.3×10^{11}	487

500 kW during 10 s
(~1% of beam lost during 10 s)



A. Ferrari, V. Vlachoudis

Cooling is essential: **T < 50 ˚C** (for outgassing)

Heat load up to 7 kW on a small area… (+ heating from upstream showers)

➔ Fix carbon-based collimator onto metallic cooling support (advanced technologies exist but expensive and long lead times: **clamping**?)

Maximum Robustness Jaws

Parameter	Unit	TCP	TCS
Azimuthal orientation		X, Y, S	various
Jaw material		C or C-C	C or C-C
Jaw length	cm	20	100
Jaw tapering	cm	2×10	2×10
Jaw dimensions	mm^2	65×25	65×25
Jaw coating		1 μm Cu	1 μm Cu
Jaw resistivity	$\mu\Omega$m	minimal	minimal
Surface roughness	μm	≤ 1	≤ 1.6
Surface flatness	μm	25	25
Heat load	kW	1.5	7
Max. operational temperature	°C	50	50
Outbaking temperature	°C	250	250
Maximum full gap	mm	60	60
Minimum full gap	mm	0.5	0.5
Knowledge of gap	μm	50	50
Jaw position control	μm	≤ 10	≤ 10
Control jaw-beam angle	μrad	≤ 15	≤ 15
Reproducibility of setting	μm	20	20
DOF movement (hor. collimator)		X, X', Y	X, X', Y
DOF movement (vert. collimator)		Y, Y', X	Y, Y', X
Positional installation accuracy	μm	100	100
Angular installation accuracy	μrad	150	150

Driving criteria for material:

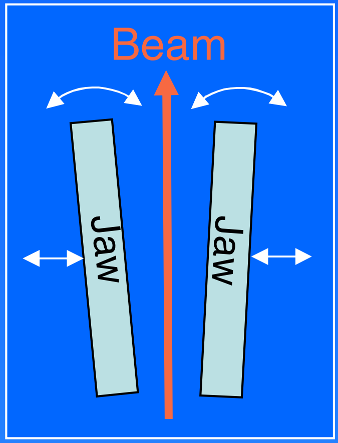
Resistivity (7-25 μΩm)
Short lead times
Samples ordered and partly arrived

Design work and prototyping under way
(EST leads effort, AB)

Choice 2: Conceptual collimator design for phase 1

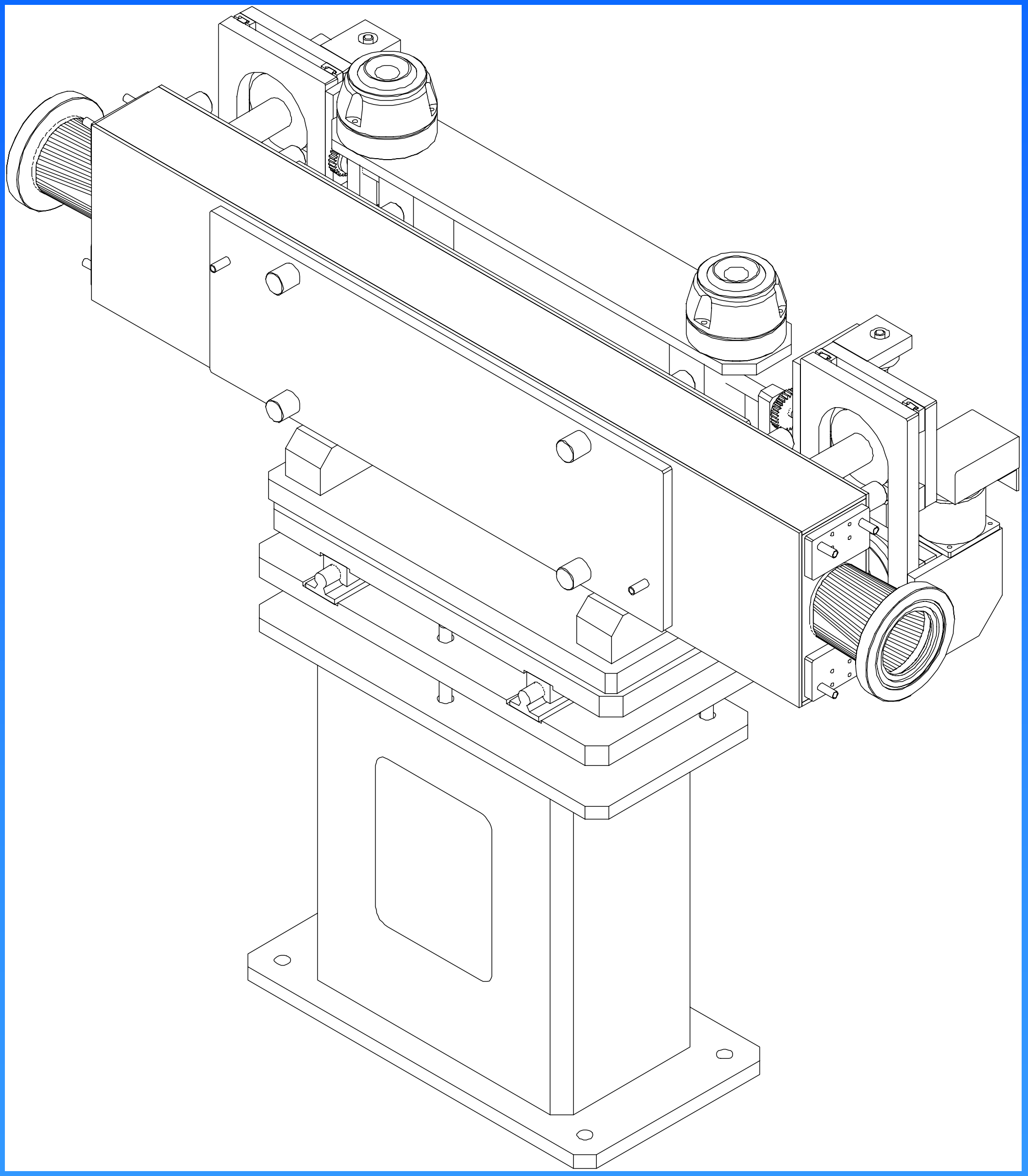
Design goals:

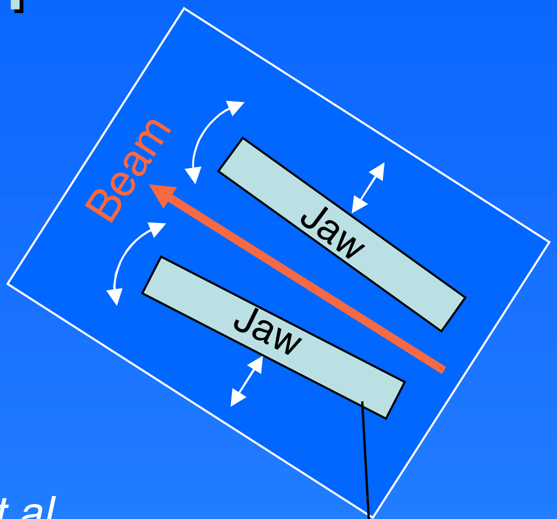
- Fit with small **inter-beam distance** of 194 mm
- Fulfill design **precision**, also with beam load (**heating**)
- **Robust** mechanics and motorization (high radiation)
- Foresee possibility of thin 1 μm coating
- **Maximum reliability** and minimum maintenance:
  - Design based on highly reliable LEP design (two jaws)
  - Concept of spare surface (move to fresh surface)
  - Jaw mechanically retracted (spring) in case of motor failure
- First 2 prototypes by **May 2004**.



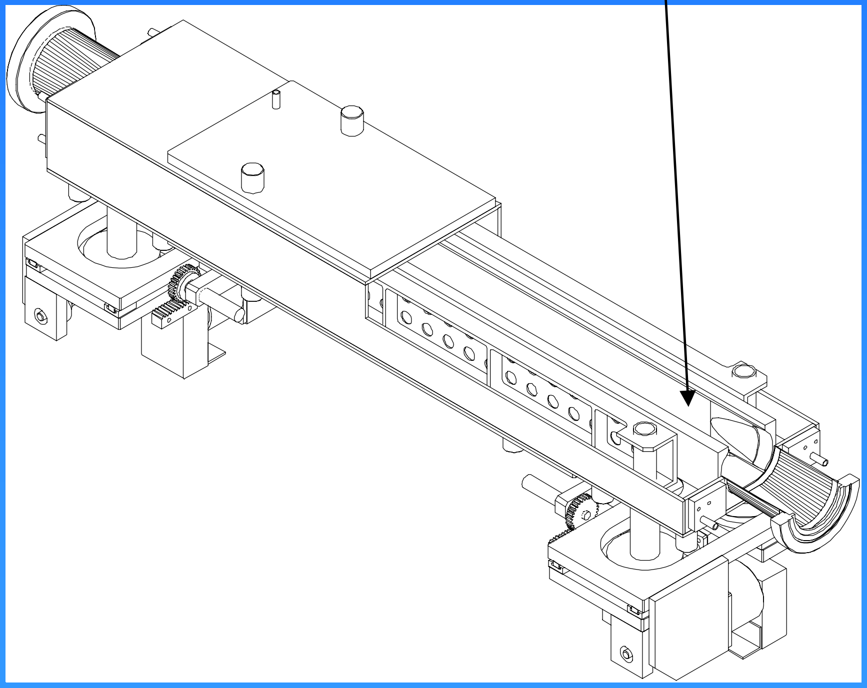
Work started with **strong EST team** in July 2003 (after decision on material and phased approach).

Drawings for prototype

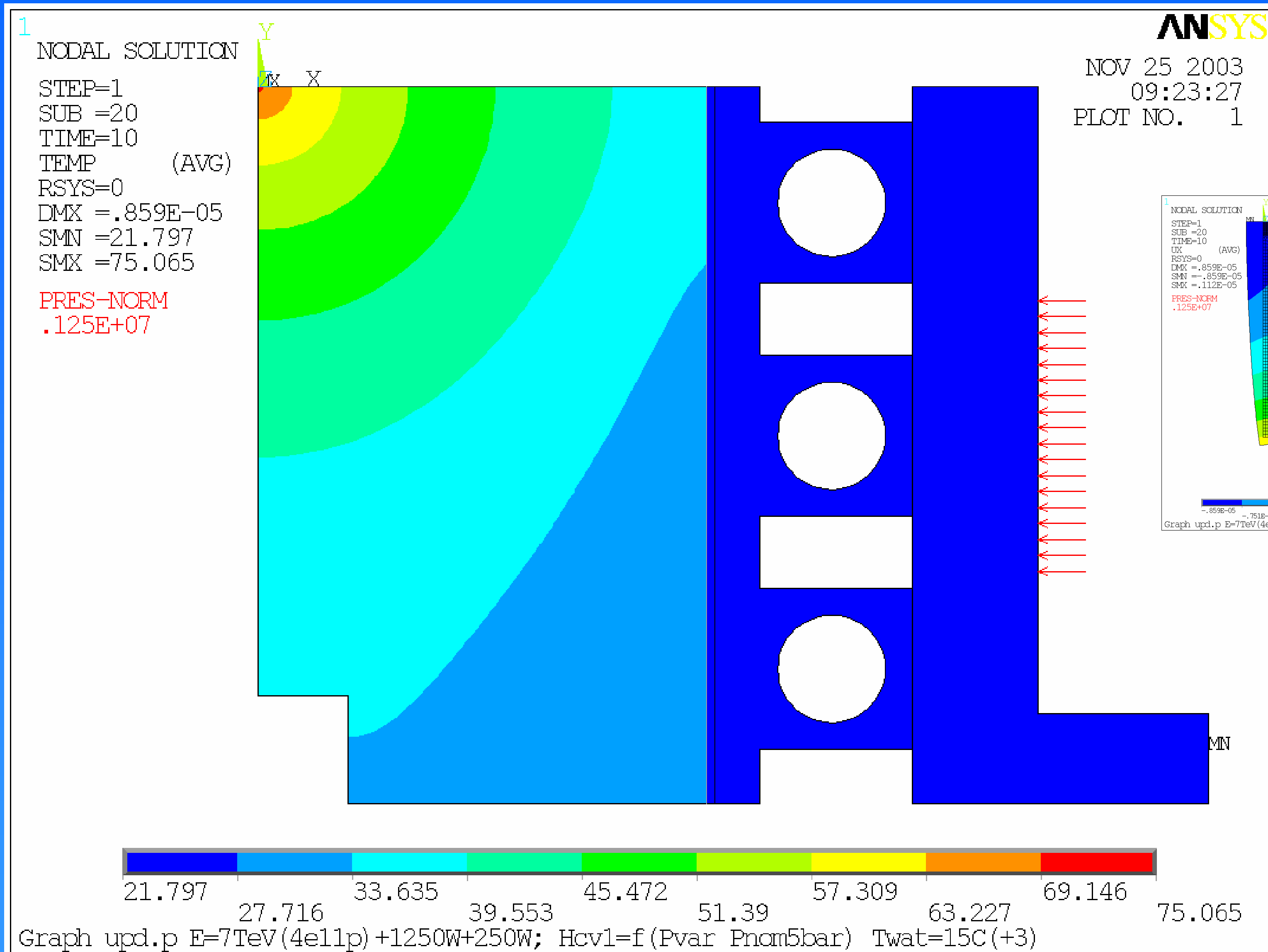


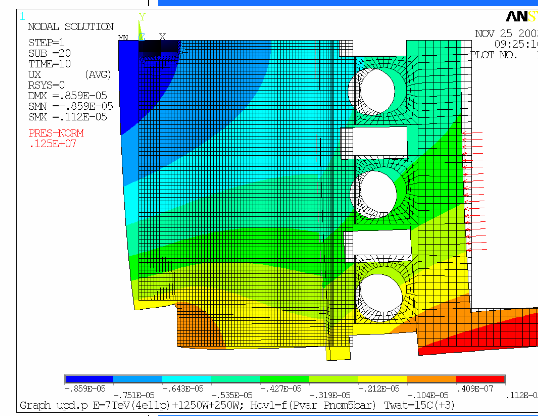


R.Perret,
A. Bertarelli et al



Design of the Collimator Cooling

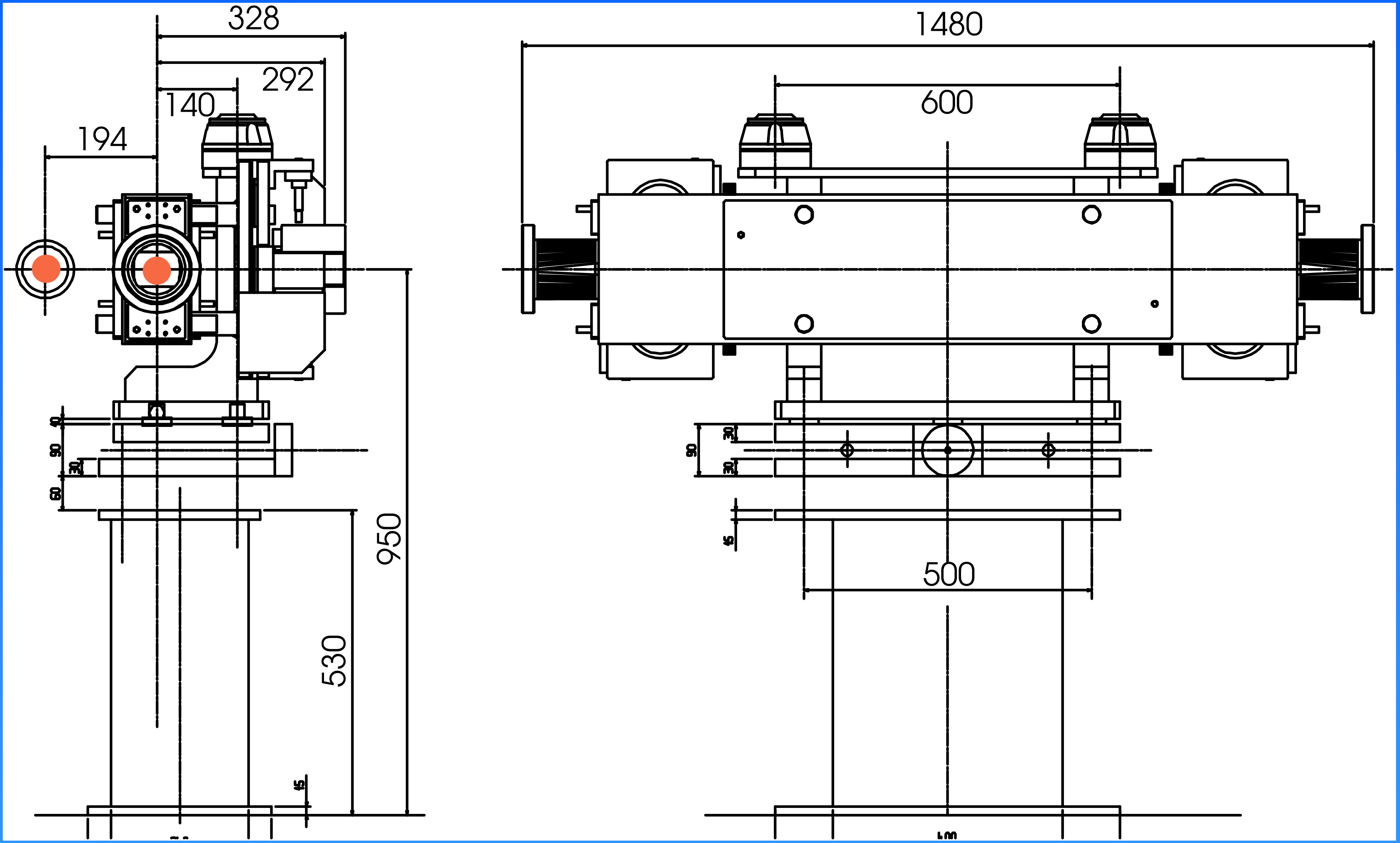




A. Bertarelli et al

Dimensions…

R.Perret, A. Bertarelli et al

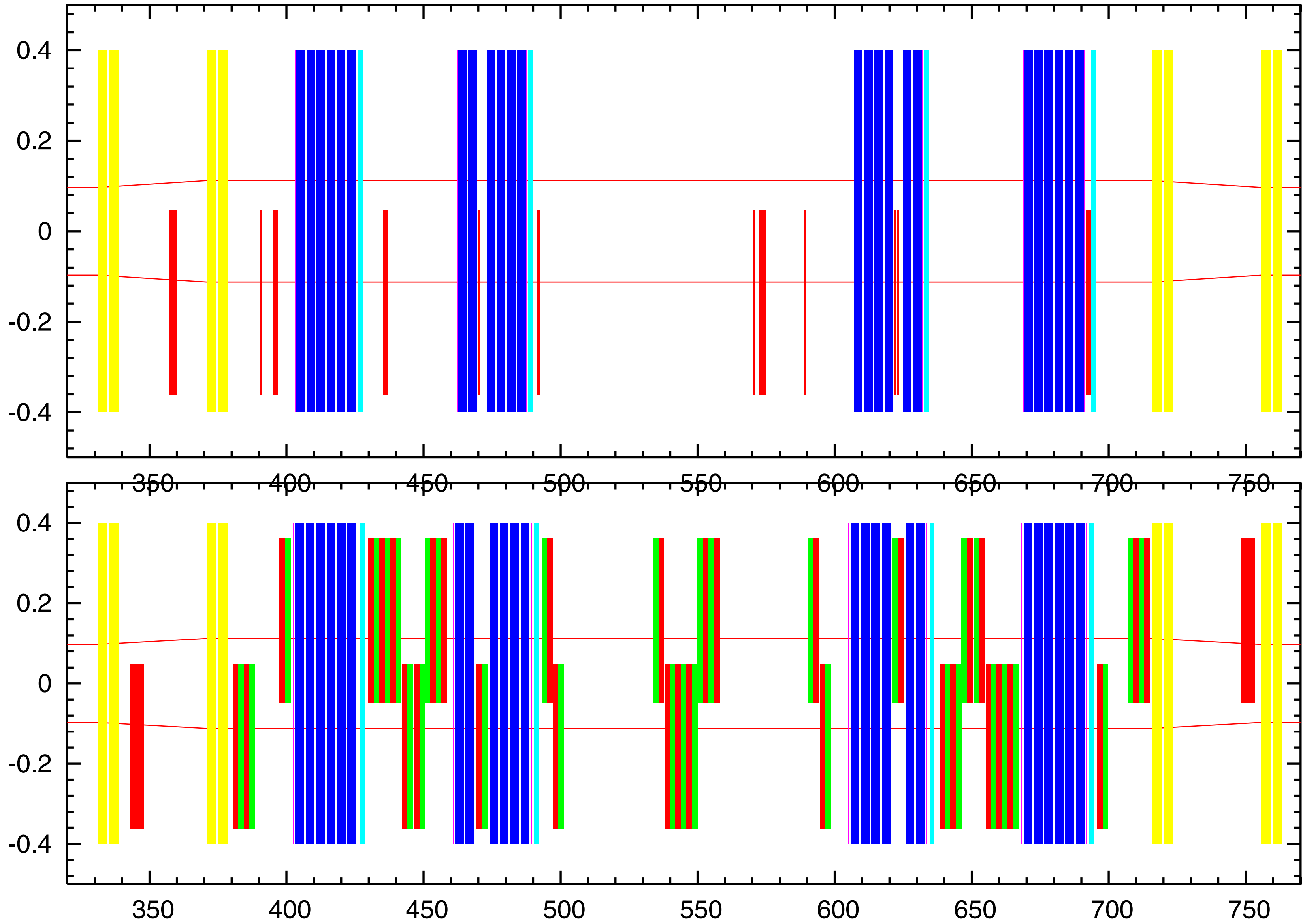


Longitudinal space per secondary collimator:	2.0 m instead of 0.7 m
Plus space for hybrid secondary collimator:	2.0 m
Total required longitudinal space:	**4.0 m** instead of 0.7 m

Choice 3: Layout of cleaning insertions

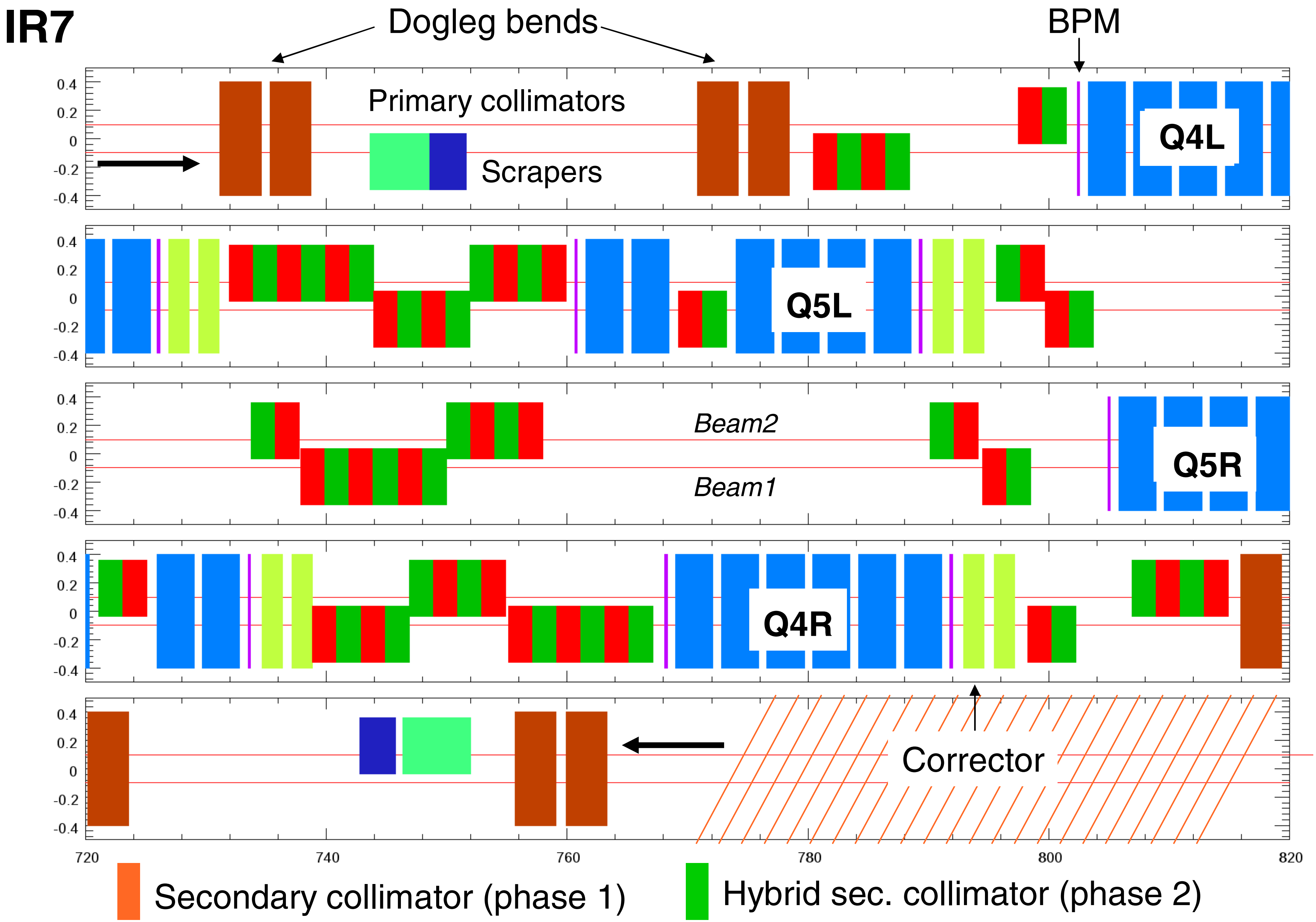
- Once longitudinal space requirements were known ➔ work on **new layouts** for IR7 (priority) and IR3.
- IR7 re-design with **new space requirements**, **efficiency optimization** and **new impedance optimization** *(difficult as space requirement went from 22m to 128m, 40% of total length)*!
- **Additional IR7 requests** from vacuum group and beam diagnostics group included at the same time.
- Proposal decided in collimator project meeting 14.11.03 and being finalized since!
- IR3 layout is being worked on. As old layout, just make **more space for the few collimators** required!

Longitudinal Layout IR7



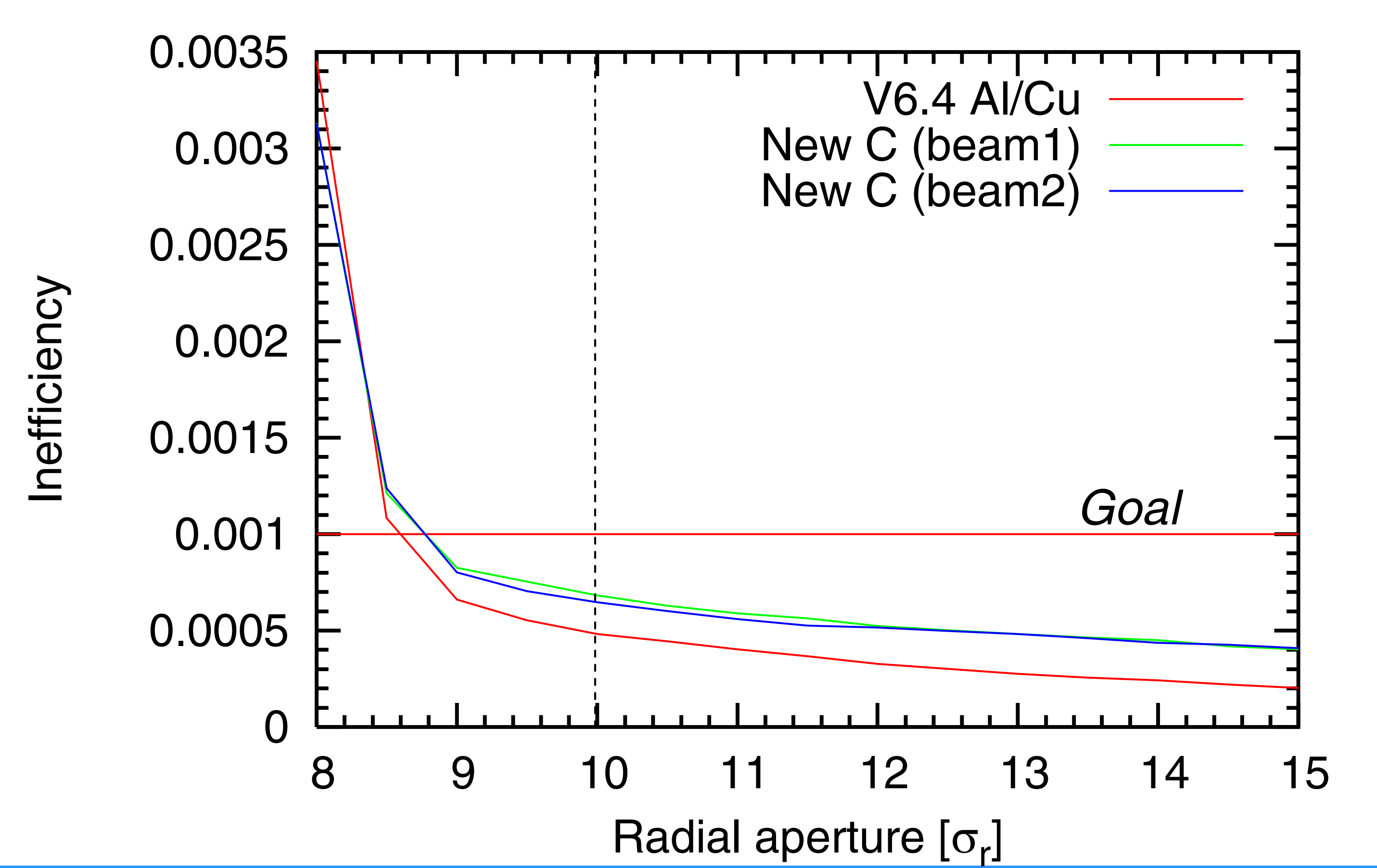
V6.4
(only beam1)

New



Quad movements up to 1m, collimator movements up to 30 m! 40% of space for collimators!

Cleaning efficiency (IR7): 7 TeV with 6/7σ



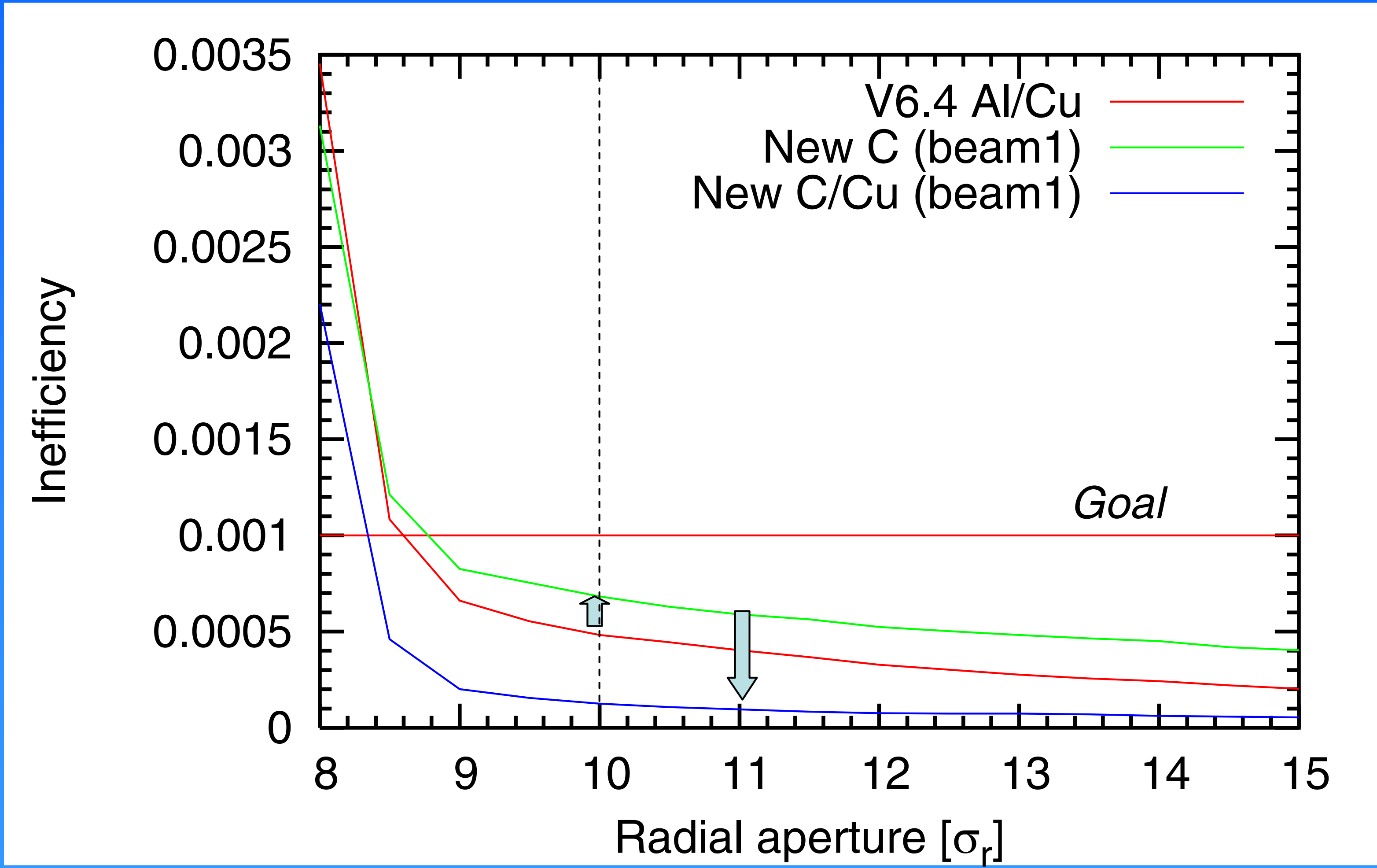
Inefficiency at 10σ about 40% higher than in old solution, but well below the target inefficiency! Beam1 and beam2 solutions show same efficiency!

Cross-check from D. Kaltchev: Amax= 9.31; Axmax = 7.25; Aymax = 7.34

(was Amax=9.41; Axmax=7.12; Aymax=7.16 with V6.4)

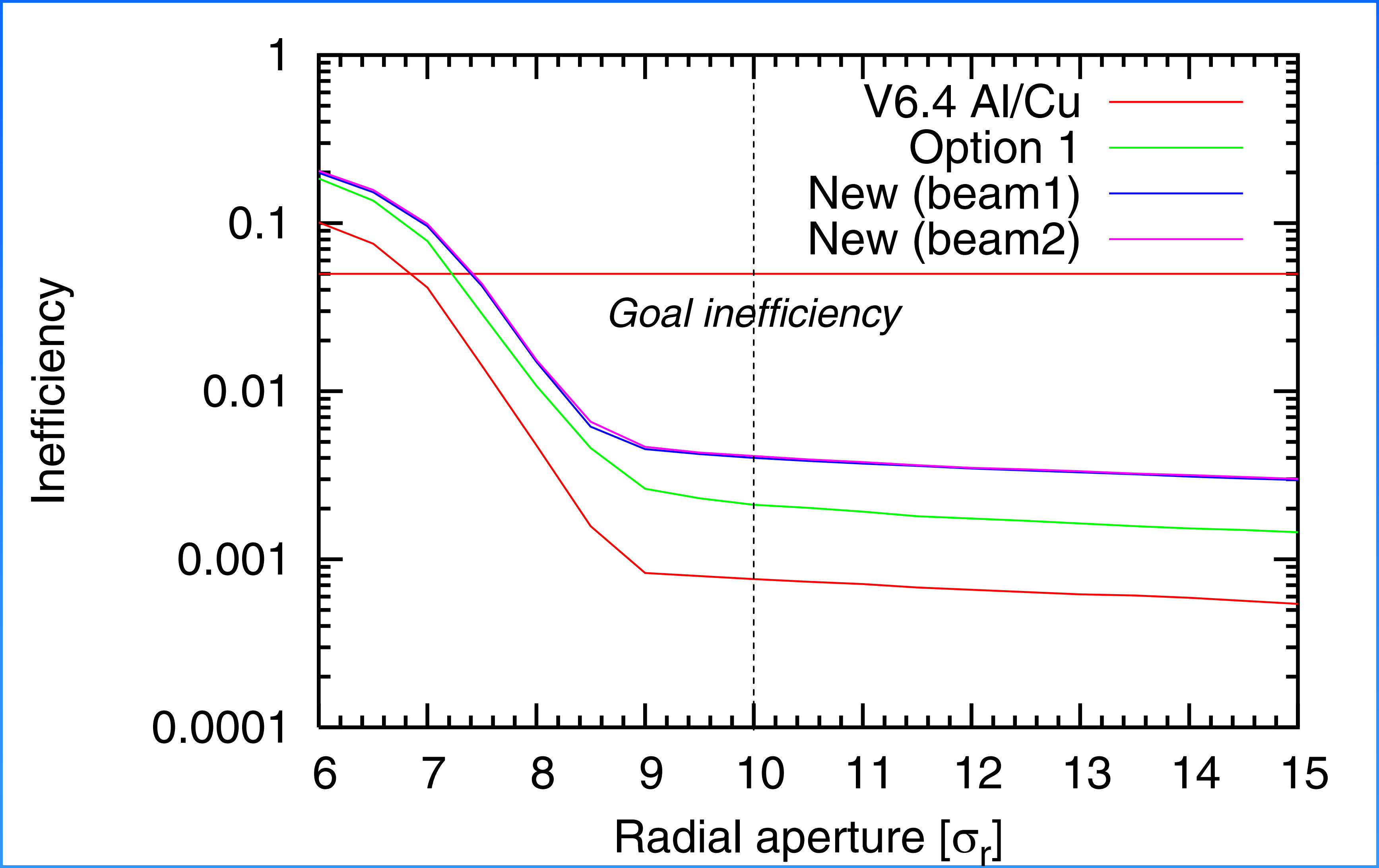
Ultimate reach IR7: 7 TeV with 6/7σ

Assuming **1m Cu secondary collimators installed in space for hybrids**:
Fixes impedance and gains efficiency (only for stable physics)!



We know how to gain a factor 7 if required! Even better than Al/Cu system!

Performance at injection with 6/7 σ

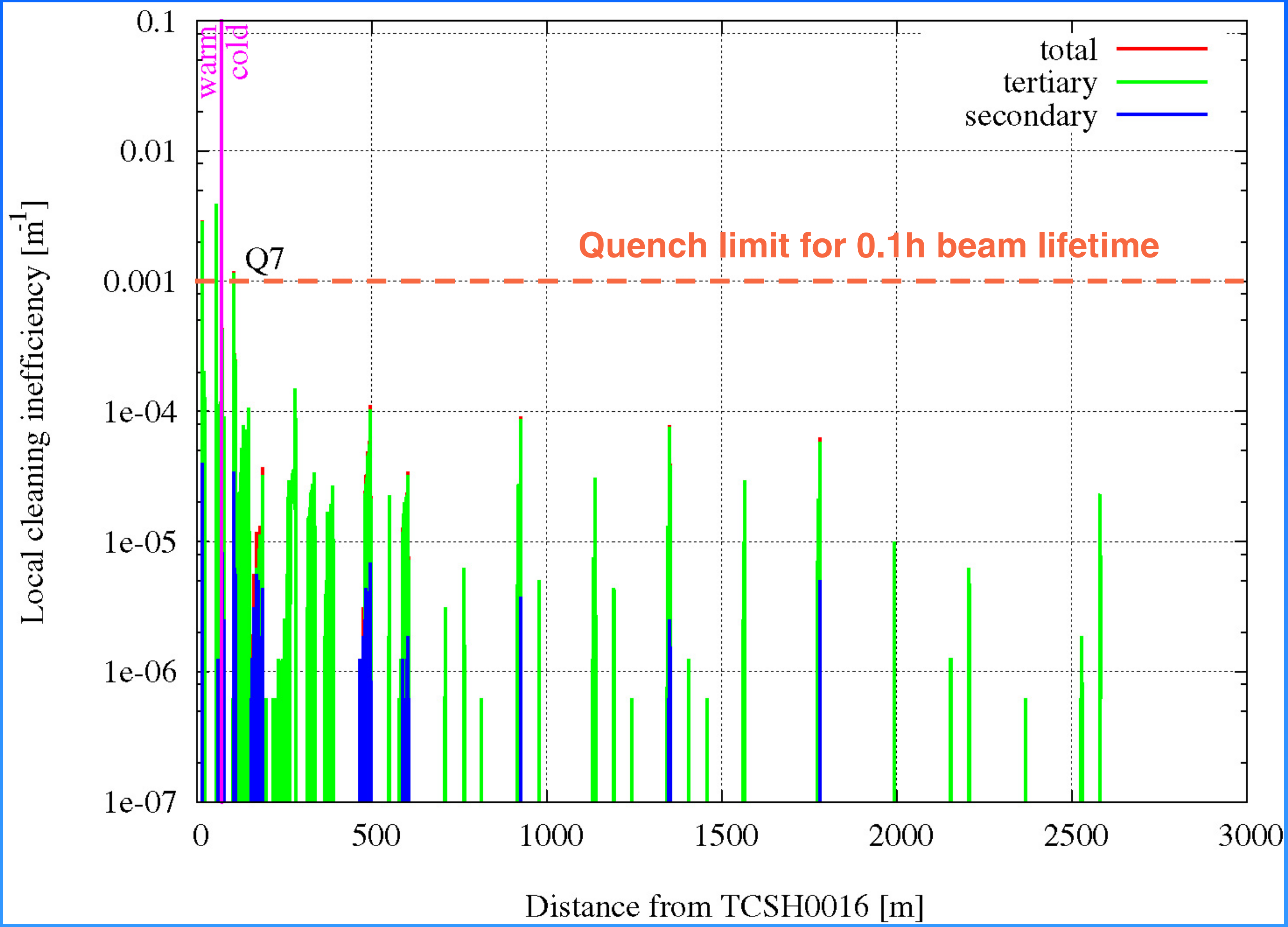


Loose factor 4 in inefficiency *(factor 2 with respect to feasible solution) but stay factor 10 below goal inefficiency!*

Detailed Calculation of Inefficiency

- Detailed aperture model with 1m resolution.
- Implemented for ~3km behind IR7 (V. Kain & B. Holzer)
- Secondary and tertiary beam halos from tracking as input (R. Assmann)
- Tracking of realistic halo through aperture model with MAD (V. Kain)
- First results for betatron cleaning at injection
- Future work:
  - Expand aperture model all around the ring.
  - More realistic collimator tracking with Sixtrack.

Local Cleaning Inefficiency 450 GeV



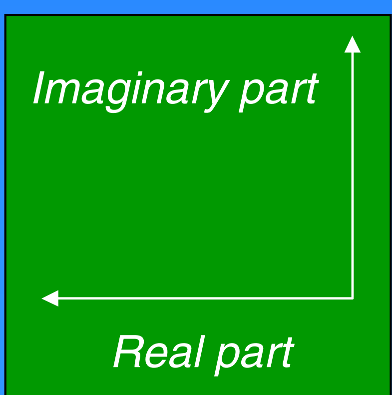
Verena Kain, Barbara Holzer, Ralph Assmann

Impedance

- January 2003: Impedance of possible graphite collimators is way too high (10 times above rest of machine).
- Stringent program for analysis in ABP collective effects team (F. Ruggiero):
  - **Analytical estimates** by L. Vos and E. Metral
  - **Full numerical simulation** by H. Tsutsui (HFSS)
  - Detailed comparisons and studies
  - **Inductive by-pass** very important
- Impedance constraints included into collimation design (phased approach) and IR7 optimization.
- Program for impedance measurements without and with beam.

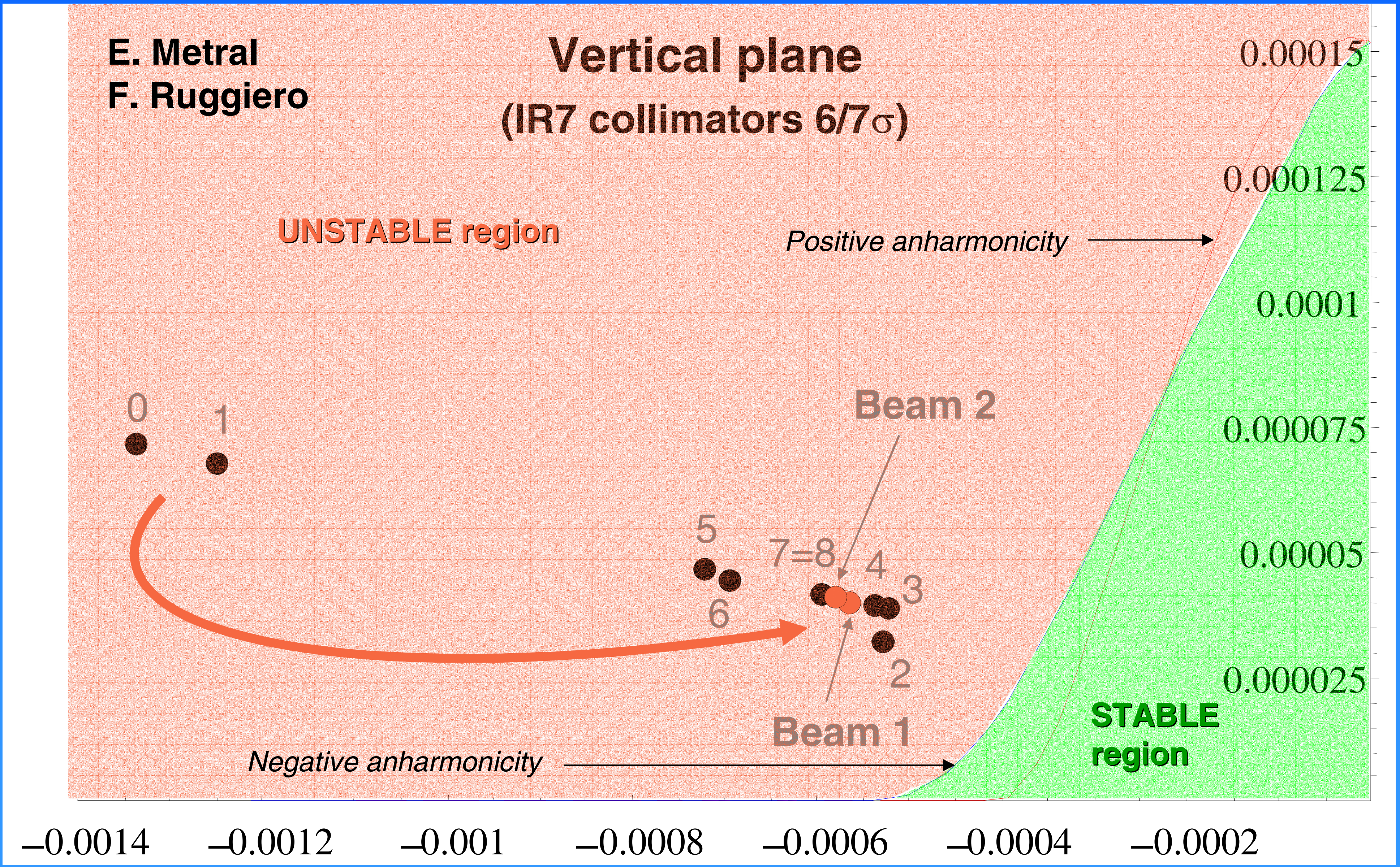
Comparing Impedance to LHC Limits

- Latest summary results by E. Metral & F. Ruggiero (in full agreement with L. Vos & H. Tsutsui)
- Limit at 450 GeV: Transverse damper.
- Limit at 7 TeV: Landau damping with maximum strength of octupoles.
- Observable: **Coherent tune shift for the most unstable coupled-bunch mode and head-tail mode 0**

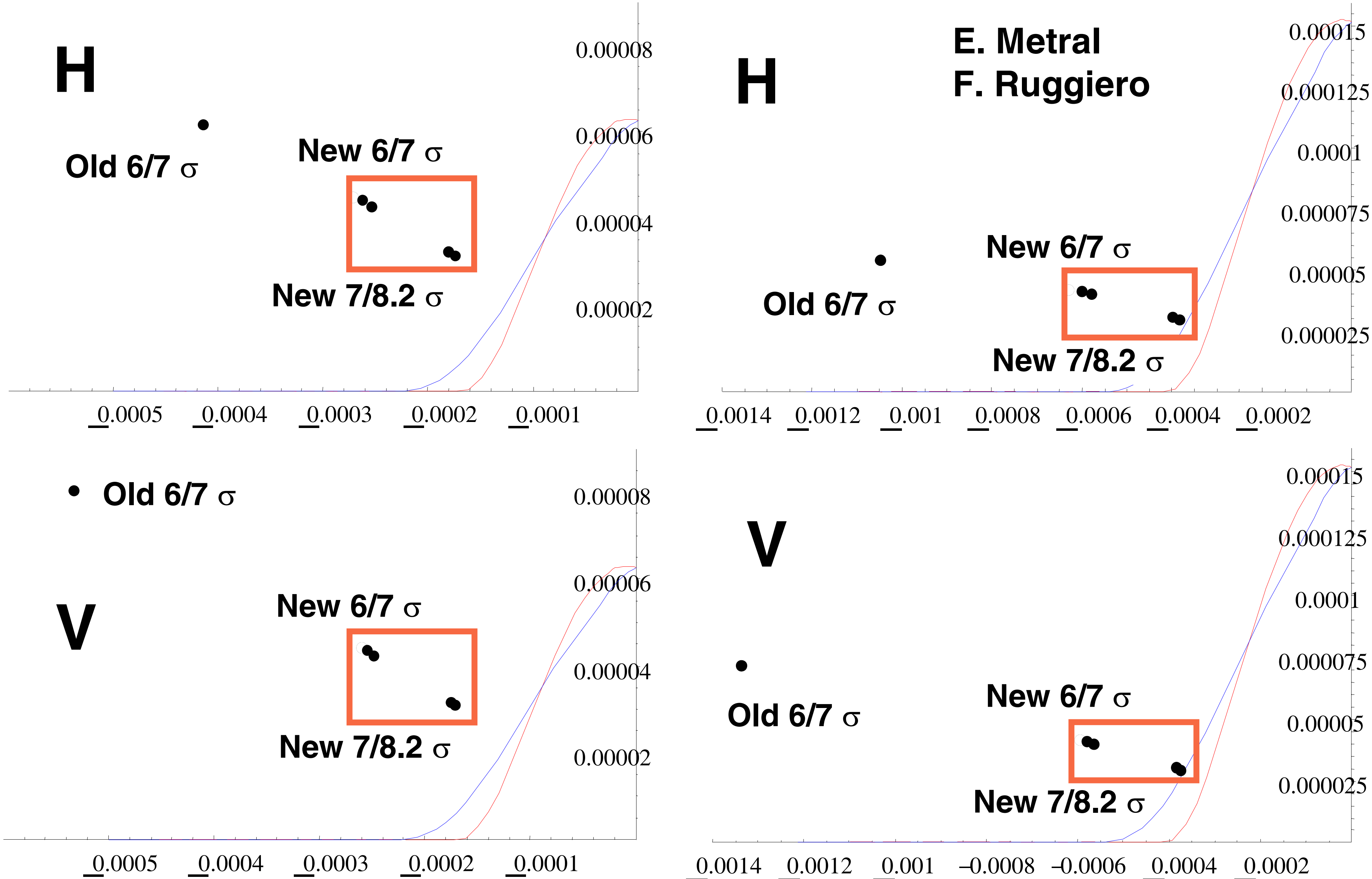


Results assume:
Nominal bunch intensity and bunch spacing.
Maximum octupole powering with either sign.

Stable and unstable regions



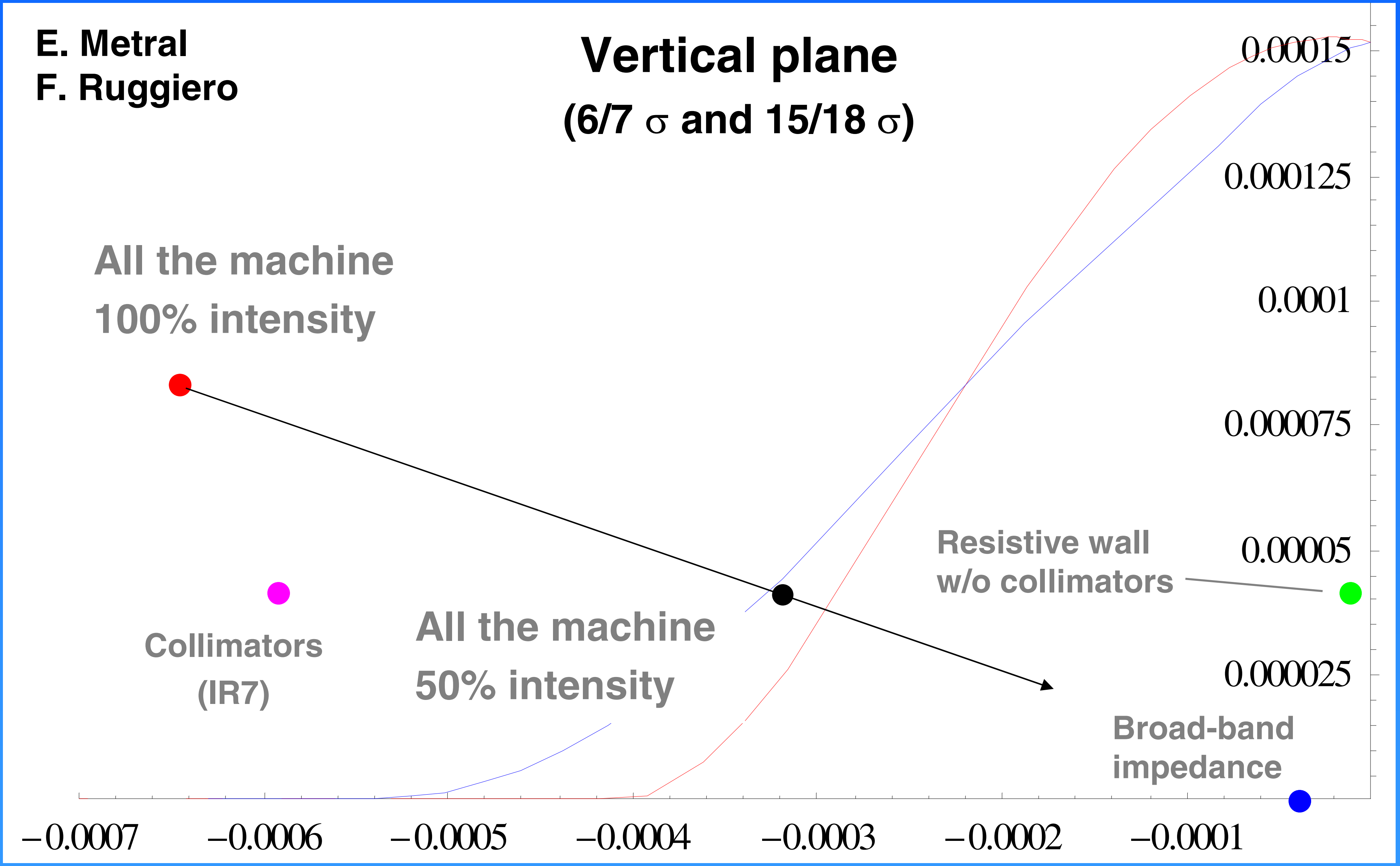
Injection (450 GeV)　　　Top (7TeV)



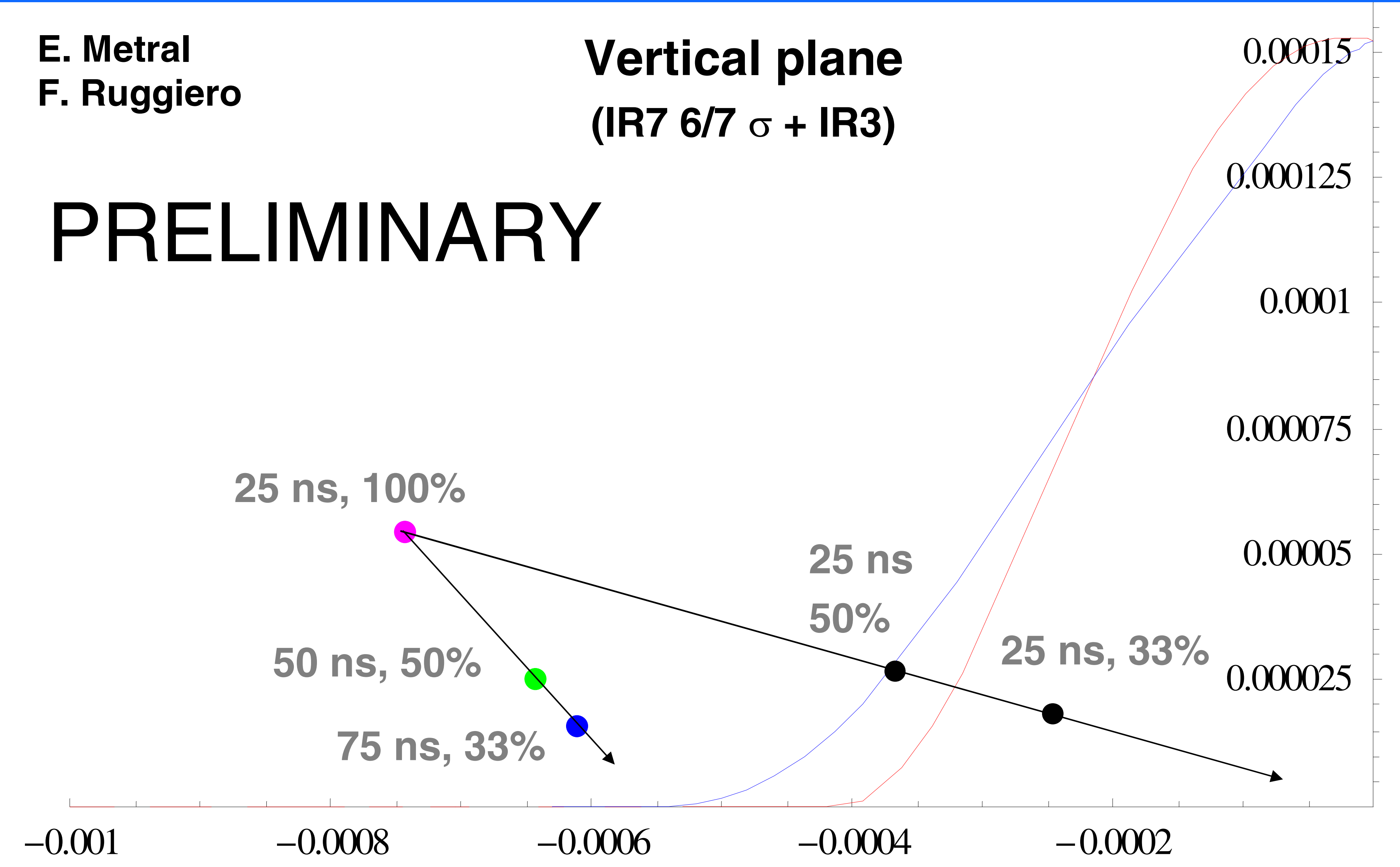
Observations

- With new IR7: Significant improvement in impedance achieved at all energies and all planes (about factor 2).
- Injection is less critical than top energy:
  → Stability is assured by transverse damper even for old impedance!
- Vertical plane is more important than horizontal plane!
- With collimators at 6/7σ in unstable regime at top energy → Limitation of intensity or β^*…
- With collimators at 7/8.2σ close to stable region…

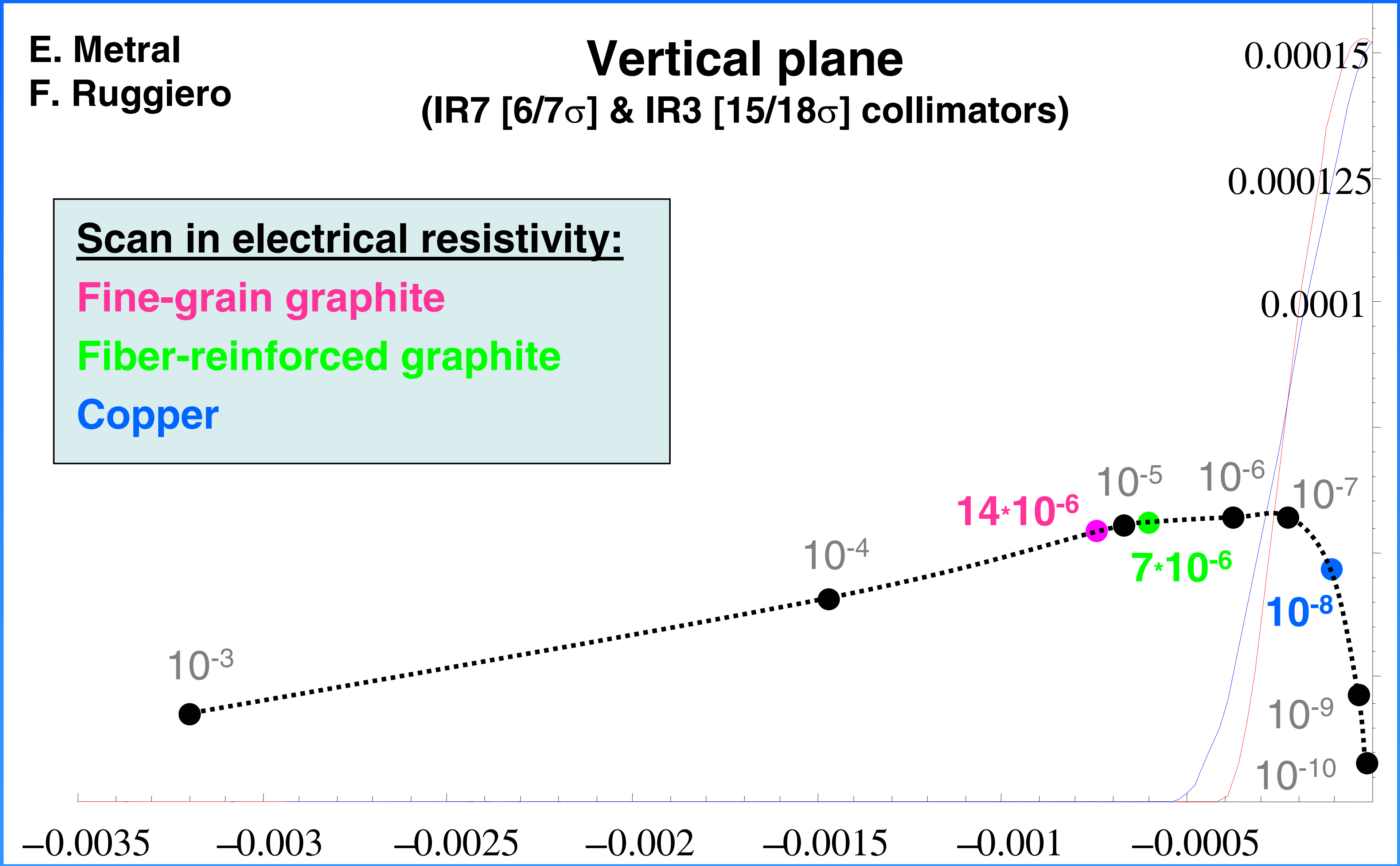
Total impedance



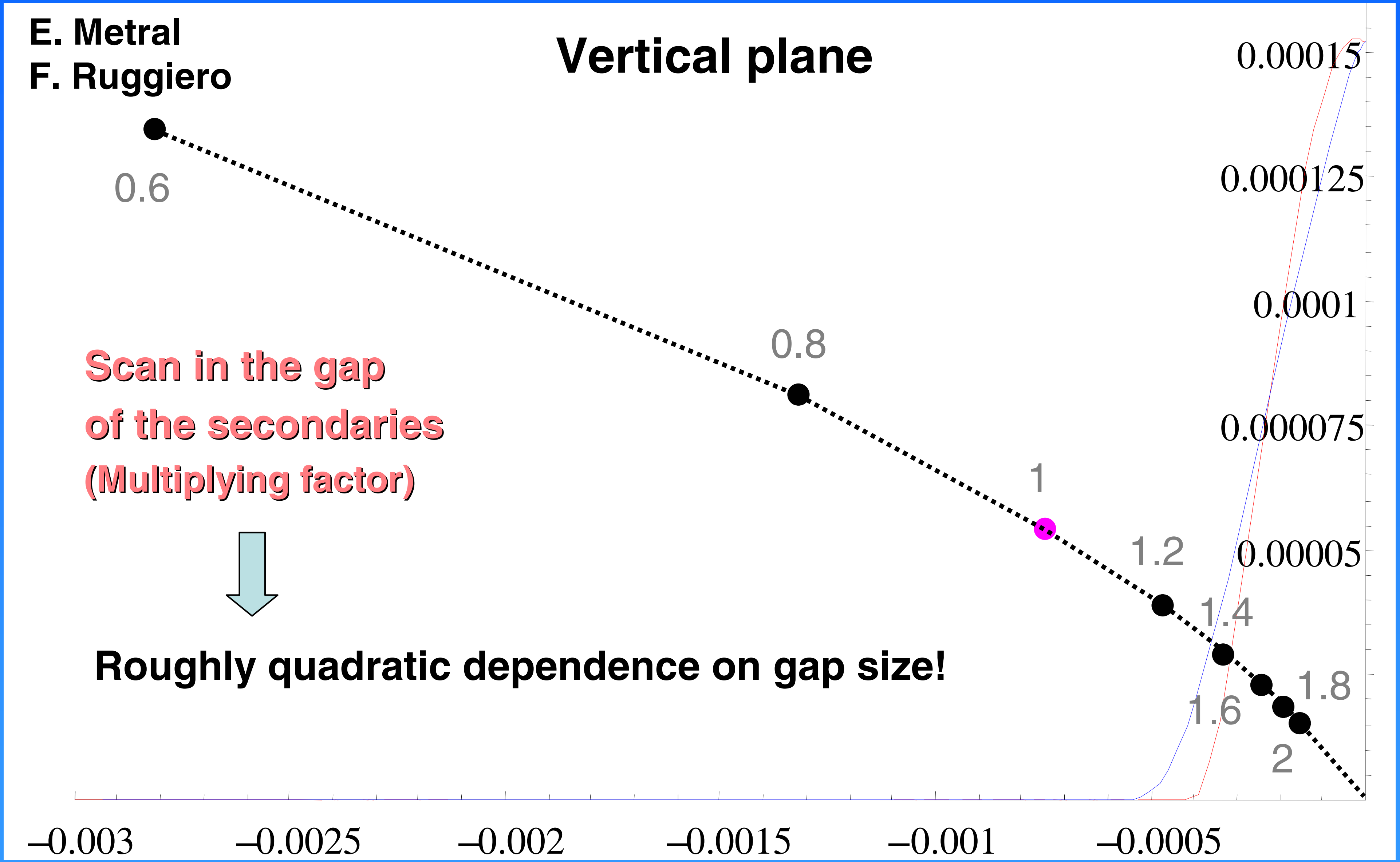
Scaling with Intensity & Bunch Spacing



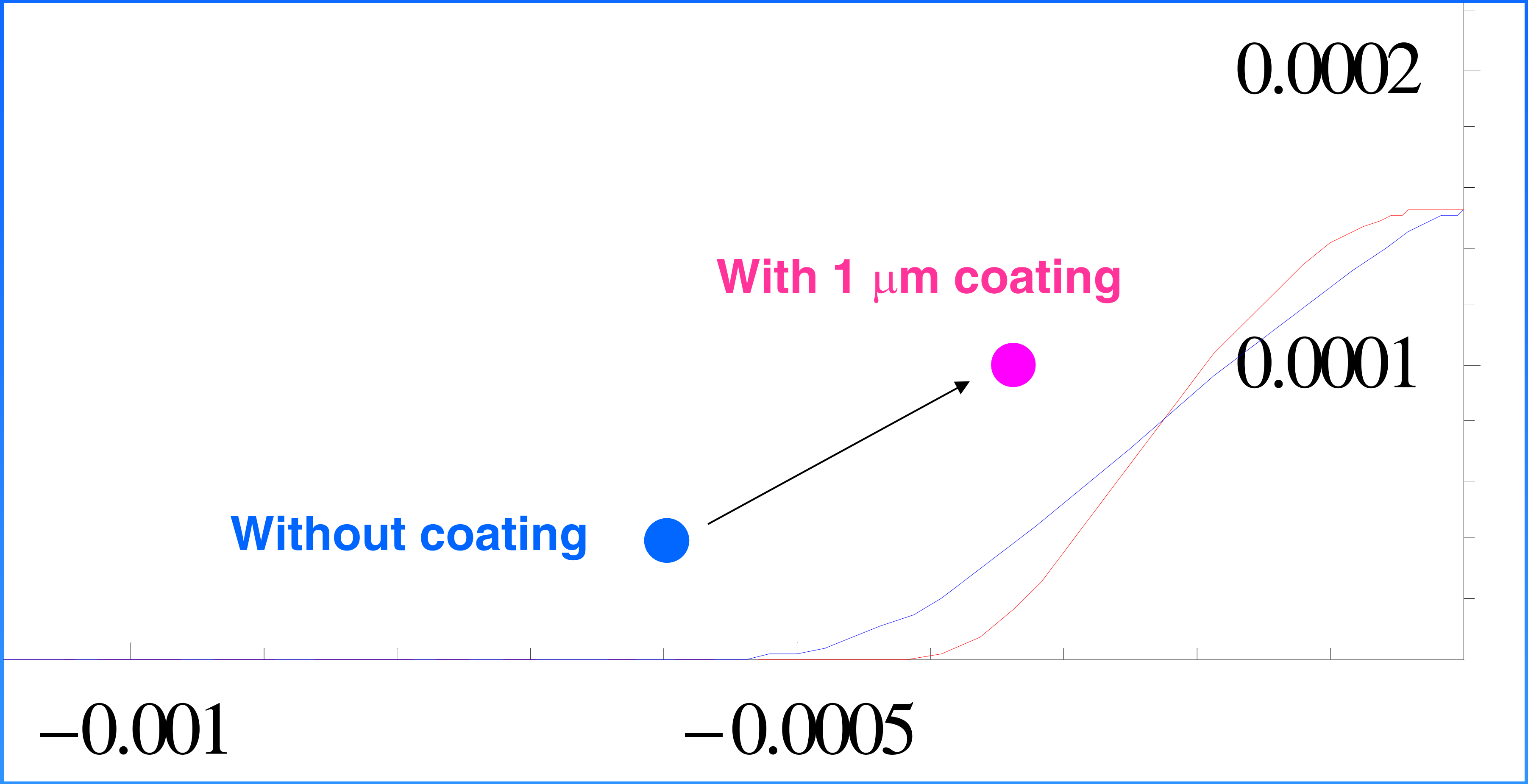
Scaling with Resistivity



Scaling with Collimator Gaps



Possible Gain with Thin Coating



Thin coating is still an option but does not solve the impedance problem!

Rely on phase 2 for low impedance!

Performance Reach Phase 1 & 2

Phase 1 collimation with new IR7 is compatible with:

- Injection up to nominal (ultimate?) intensities.
- Commissioning.
- Physics during the first years of the LHC (up to ~50% of nominal intensity with nominal β^*).
- Maximum uptime due to best possible robustness.

Phase 2 collimation can have (assuming Cu):

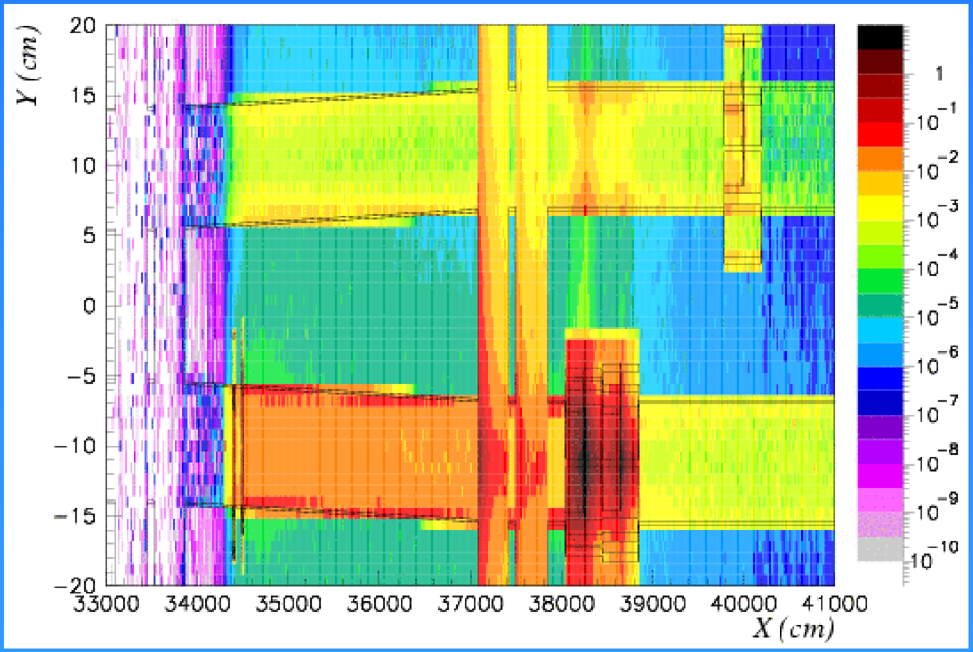
- 6 times lower impedance.
- 7 times better cleaning efficiency.
- Allow nominal and ultimate performance.

Future choices

A few important choices are ahead of us:

- **Absorbers** to intercept showers (~ 100's kW). ~ *May 2004*
- **Shielding** for optimization of radiation impact. ~ *May 2004*
- **Motorization and local control** for up to 500 motors. ~ *June 2004*

Work has started, e.g. for collimator heat load in IR7:



V. Vlachoudis, A. Ferrari

Prototyping & Testing

- Heating and cooling test early January 2004.
- Full prototypes for secondary collimators in May 2004.
- 2 months testing in laboratory (mechanics, tolerances, impedance, vacuum, …).
- Installation into SPS and TT40 in August 2004.
- TT40: Robustness against full LHC batch (design case).
- SPS: Functional test, adjustments to beam with 3mm gap, impedance, loss maps, …
- Results by November 2004!

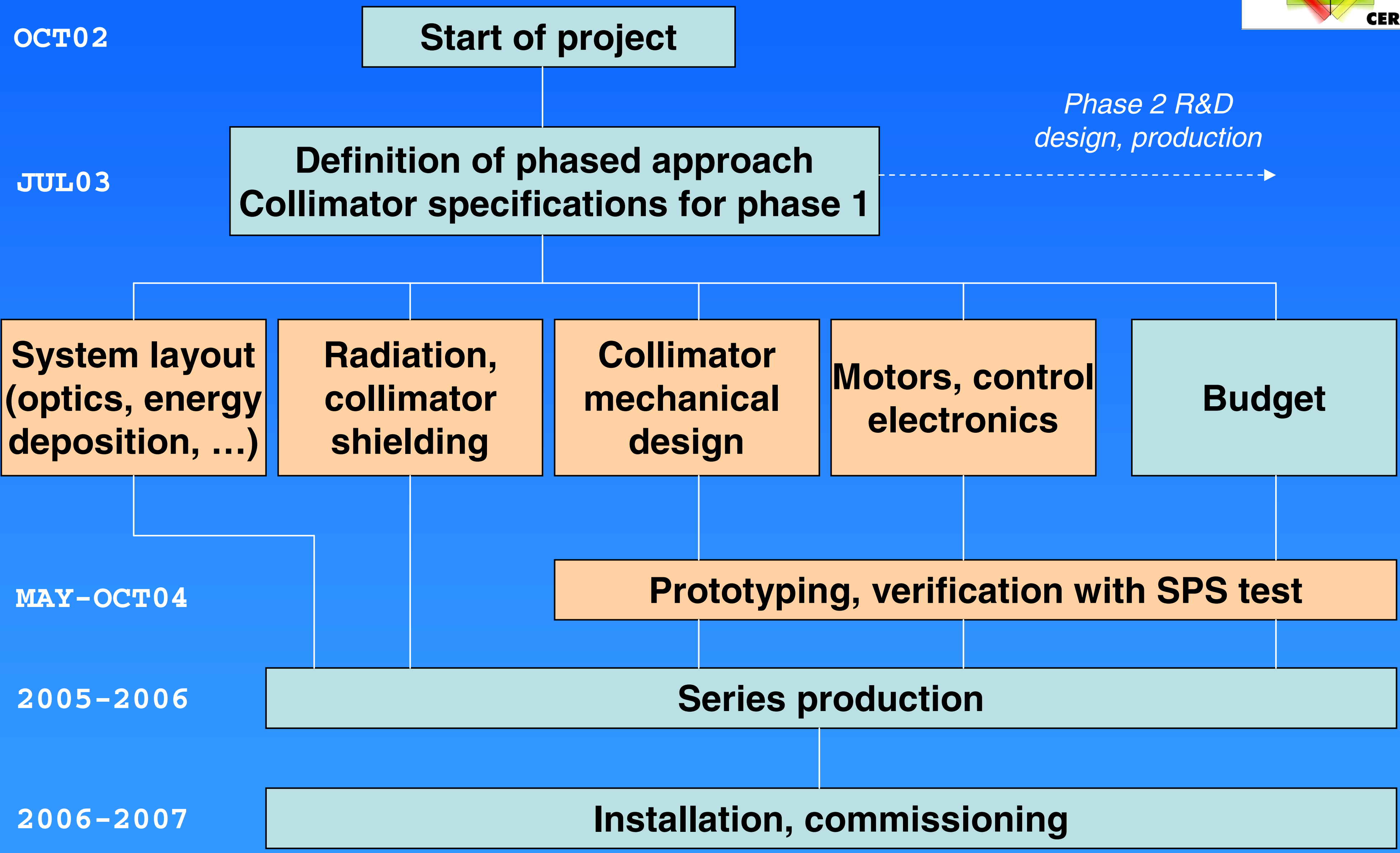
Series Production

- Series production of 79-95 components until middle of 2006 is a challenge.
- Preparation of series production must start in January 2004 (market survey, …).
- Goal:
  - **Final functional description** by June 2004.
  - **International review** of the collimation project at CERN after EPAC04.
  - **Final drawings** in Summer 2004.
  - Submission to **Finance Committee** for approval of order in December 2004.

Summary and Outlook

- A phased approach was adapted to provide a path to ultimate performance while respecting the LHC schedule:
  - **Minimum initial cost and effort**
  - Large **flexibility** to profit from LHC learning curve (“the real problems?”)
  - Room for upgrades
- Phase 1 collimation:
  - maximum robustness with graphite-based jaws
  - operated at the impedance limit, **supporting up to 50% of nominal intensity** with nominal β^*.
- IR7 re-design (IR3 to follow before Christmas):
  - **space for all phases**
  - **better reach in efficiency**
  - **lower impedance**
- Collimator design for phase 1 is well advanced:
  - **Conventional design** based on LEP experience
  - **First prototypes** in May 2004
- Some remaining decisions: Absorbers, shielding, motorization & local control
- International review of collimation project after EPAC04.
- Validation tests with and without beam from January-November 2004.
- Planning for ordering in time for finance committee in December 2004.

Main work flow



Project steering
E. Chiaveri

Collimation project
Leader: ***R. Assmann***
Project engineer: ***O. Aberle***
Organization, schedule, budget, milestones, progress monitoring, design decisions

report to

AB division
(S. Myers, LTC)

LHC project
(L. Evans)

Resources/planning
R. Assmann, E. Chiaveri, M. Mayer, J.P. Riunaud

Supply & ordering
O. Aberle, A. Bertarelli

Beam aspects
R. Assmann, LCWG
System design, optics, efficiency, impedance (calculation, measure-ment), beam impact, tolerances, diffusion, beam loss, beam tests, beam commissioning, functional specification (8/03), operational scenarios, support of operation

Energy deposition, radiation
A. Ferrari
(collimator design, ions)
J.B Jeanneret
(BLM's, tuning)
M. Brugger
(radiation impact)
FLUKA, Mars studies for energy deposition around the rings. Activation and handling requirements.

Collimator engineering & HW support
O. Aberle
Sen. advice: P. Sievers
Conceptual collimator de-sign, ANSYS studies, hardware commissioning, support for beam tests, series production, installation, maintenance/repair, electronics&local control, phase 2 collimator R&D

Mechanical eng-ineering (EST)
Coord.: M. Mayer
Engin.: A. Bertarelli
Sen. designer: R. Perret
Technical specification, space budget and mecha-nical integration, thermo-mechanical calculations and tests, collimator mechanical design, prototype testing, prototype production, drawings for series production.

Machine Protection	**Vacuum**	**Beam instrum.**	**Dump/kickers**	**Integration into operation**
R. Schmidt	*M. Jimenez*	*B. Dehning*	*B. Goddard*	*M. Lamont*

Local feedback	**Controls**	**Electronics/radiation**
J. Wenninger	*AB/CO*	*T. Wijnands*