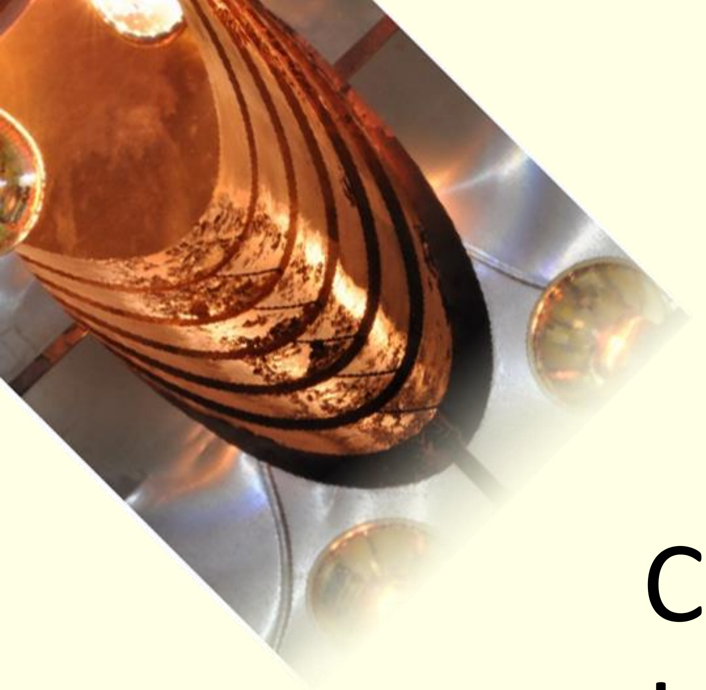
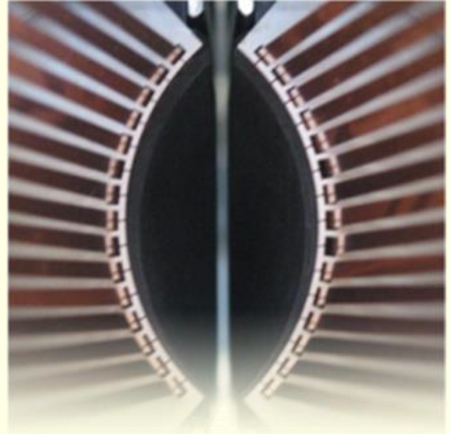
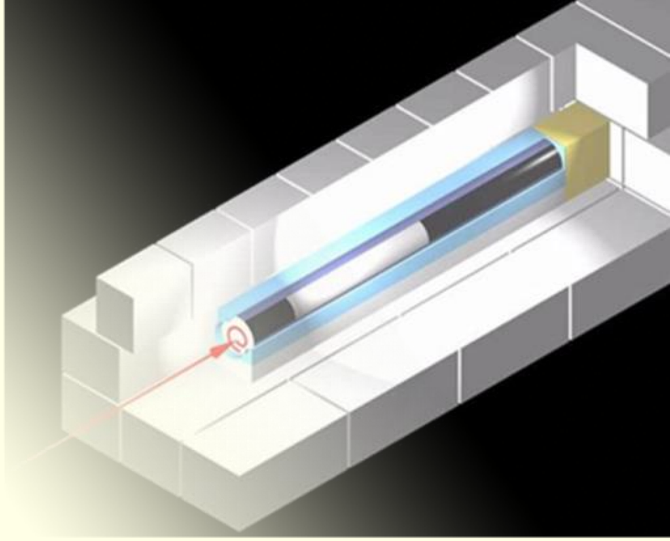
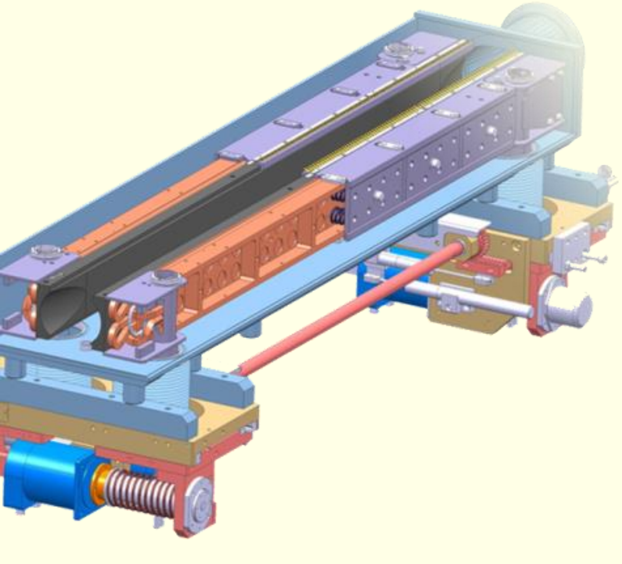


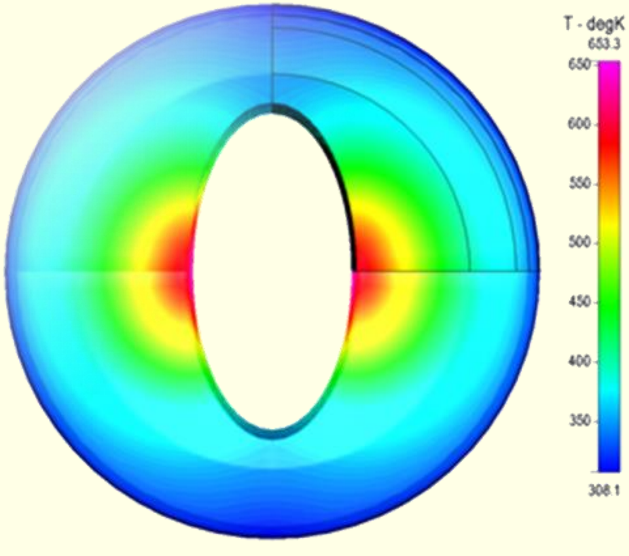




Collimation and Beam Dumps

Mike Seidel, PSI



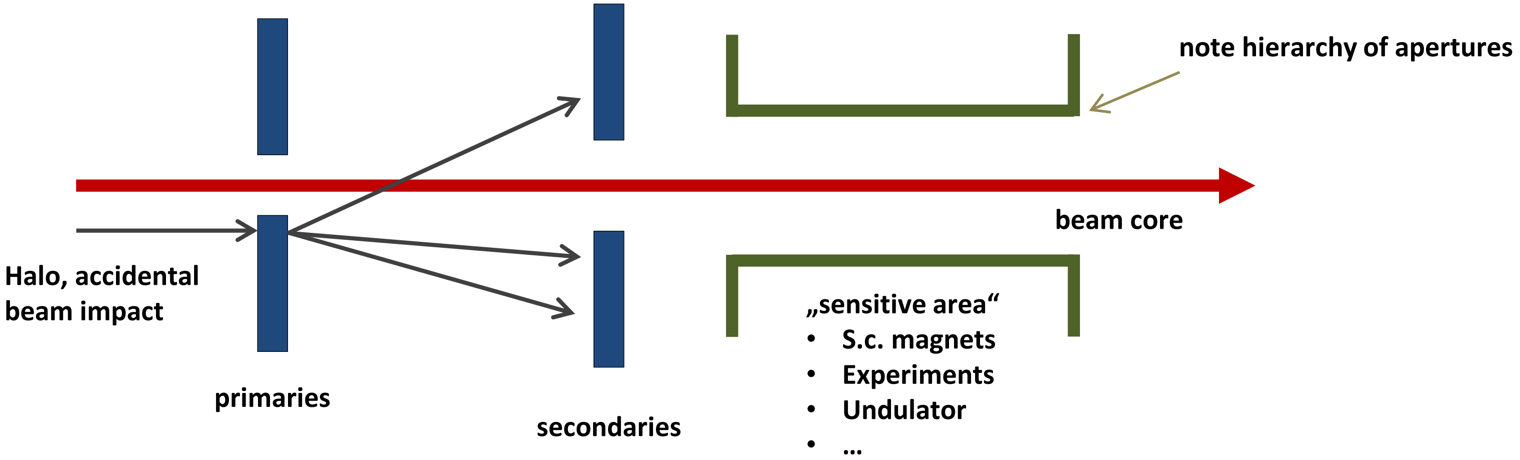


Outline

- Introduction: Purpose and application of collimation
  - quick examples: LHC, ILC, PSI-HIPA, E-XFEL
- Beam collimation, a multi-physics problem
  - Beam dynamics: halo diffusion & impact parameter
  - Beam dynamics: scattering & multi stage collimation
  - Beam material interaction, thermo-mechanics
  - Wakefields/Impedance
- Beam Dumps
  - Purpose of dumps for different facilities
  - Example implementations

The purpose of collimation

- remove particles beyond $n \times \sigma$ (transverse & longitudinal)
- localize losses at suited locations, provide operational tolerance for temporary “tuning” situations with high losses, avoid activation, quench, detector background [continuous loss, standard operation]
- protect machine from sudden beam loss, e.g. magnet failure [accidental loss]
- provide diagnostics by probing the beam, loss detection



In which facilities do we need collimation ?

Typical use cases for collimators

- collimation in a **ring collider** with hadron beams
- collimation in **linear colliders** with highly focused electron/positron beams
- other **high intensity hadron** accelerators like cyclotrons
- applications for single passage collimation, i.e. for injected beams
- collimators and masks for synchrotron light in electron rings

Next slides: examples of different collimation systems

- Large Hadron Collider
- Linear Collider Final Focus Collimation
- CW High Intensity Proton Accelerator
- Post-Linac Collimation for EXFEL

Layout of LHC collimation system

Two warm cleaning insertions,
3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

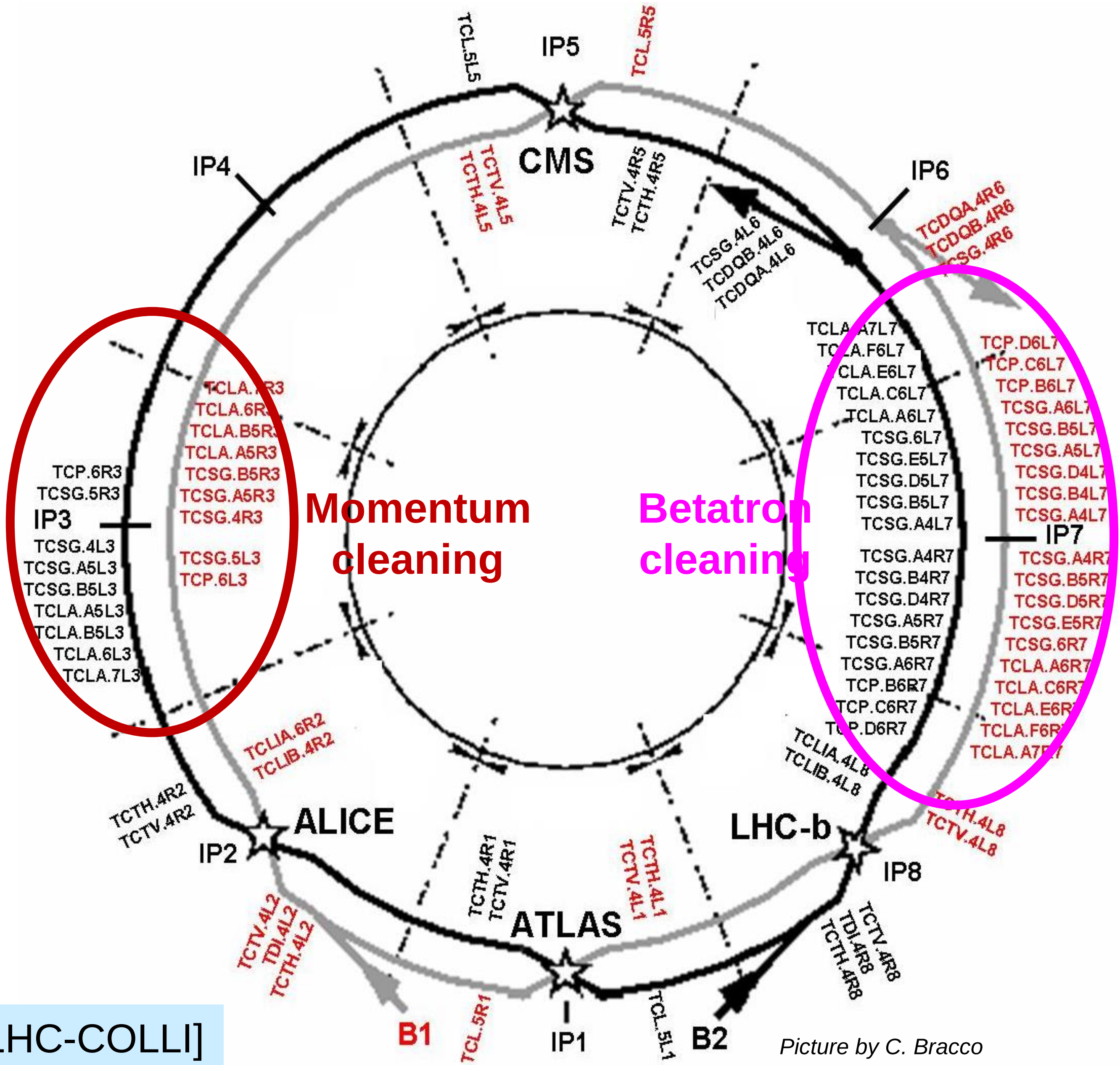
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

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

Total of 108 collimators (100 movable). Two jaws (4 motors) per collimator!

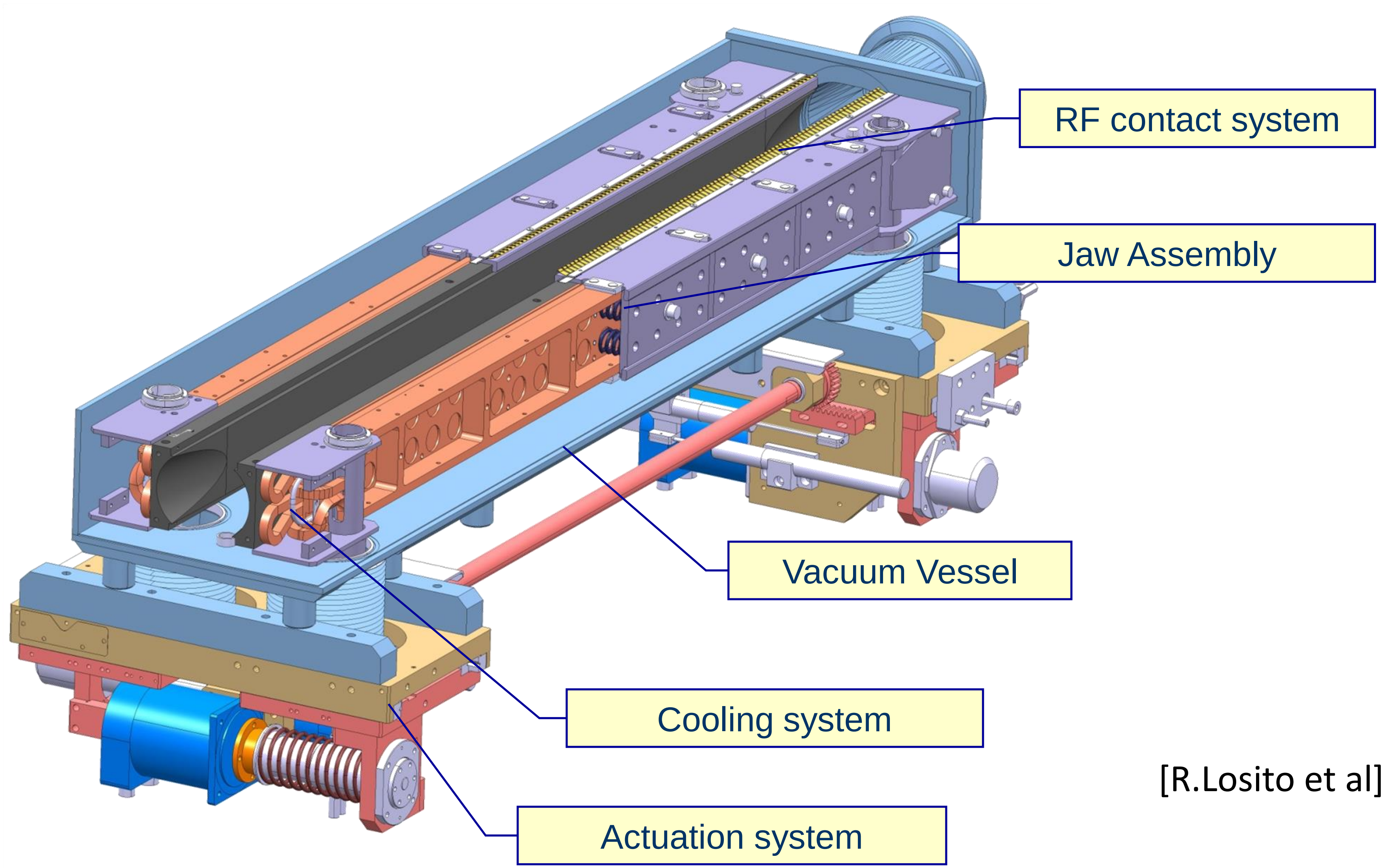


Picture by C. Bracco

[LHC-COLLI]

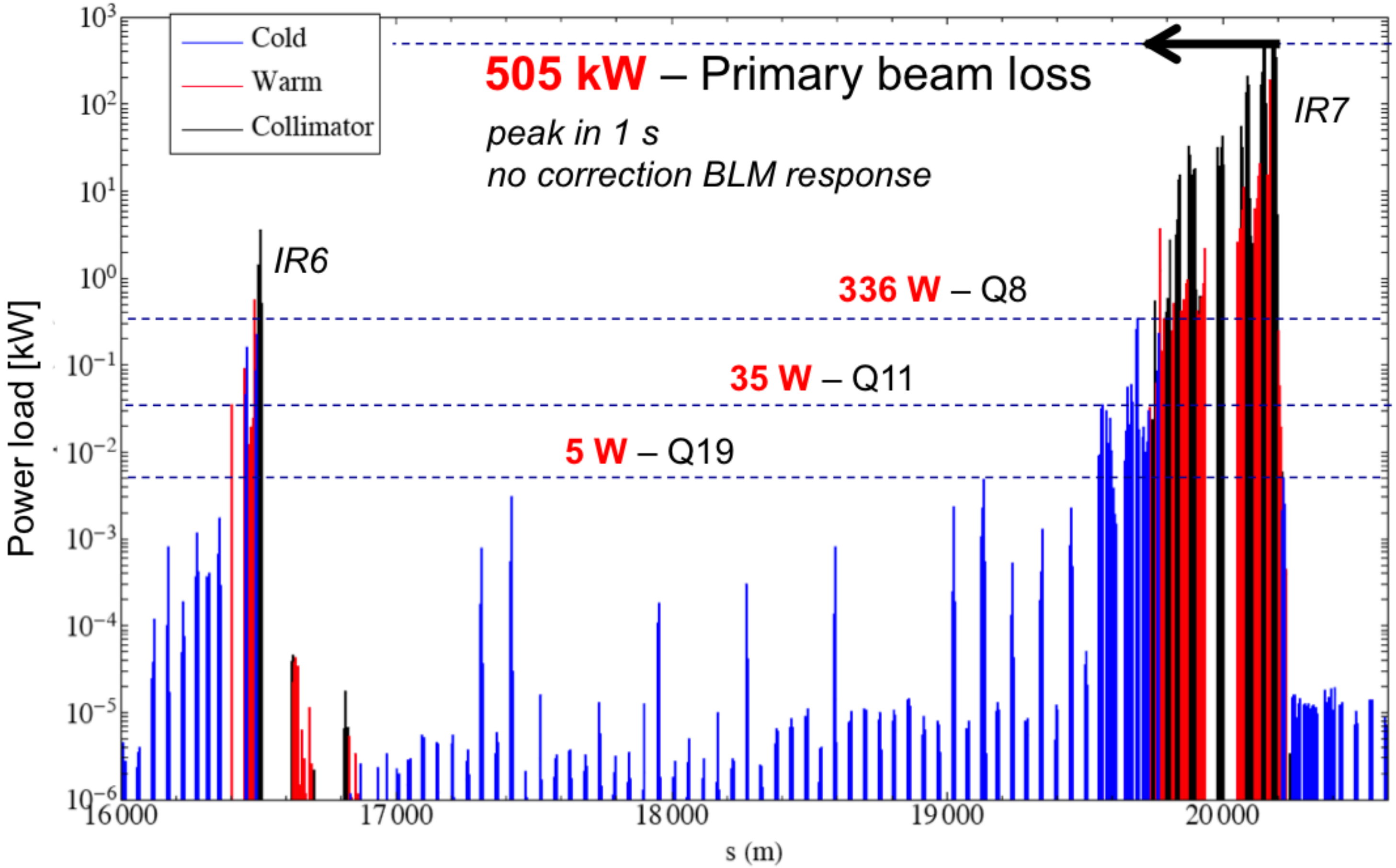
S. Redaelli, CollReview, 14-06-2011

CERN LHC Collimator Design



[R.Losito et al]

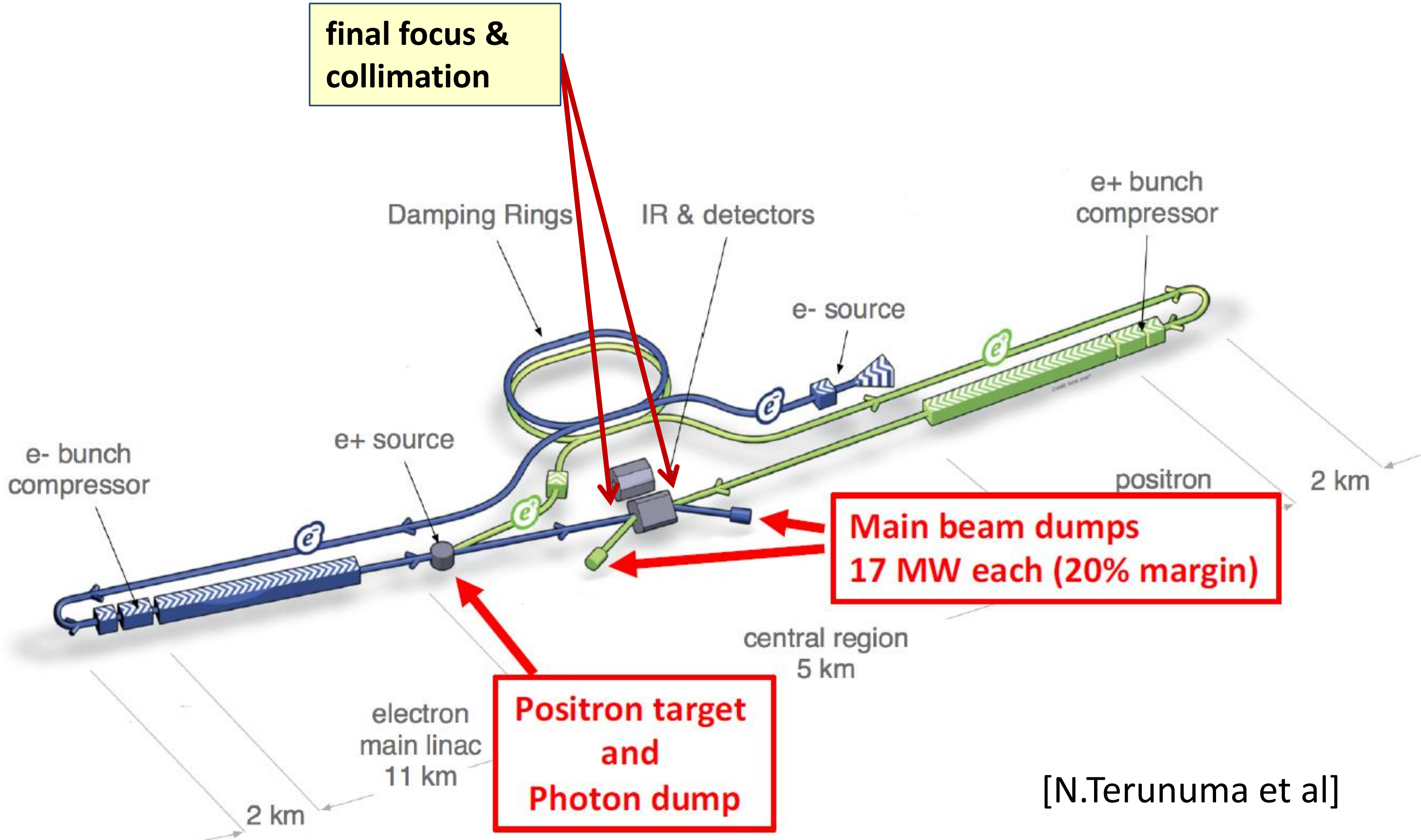
LHC: Collimation of High Power Loss



[courtesy: CERN collimation team]

Example of artificial high loss test, 4TeV, no quench!

Example: International Linear Collider

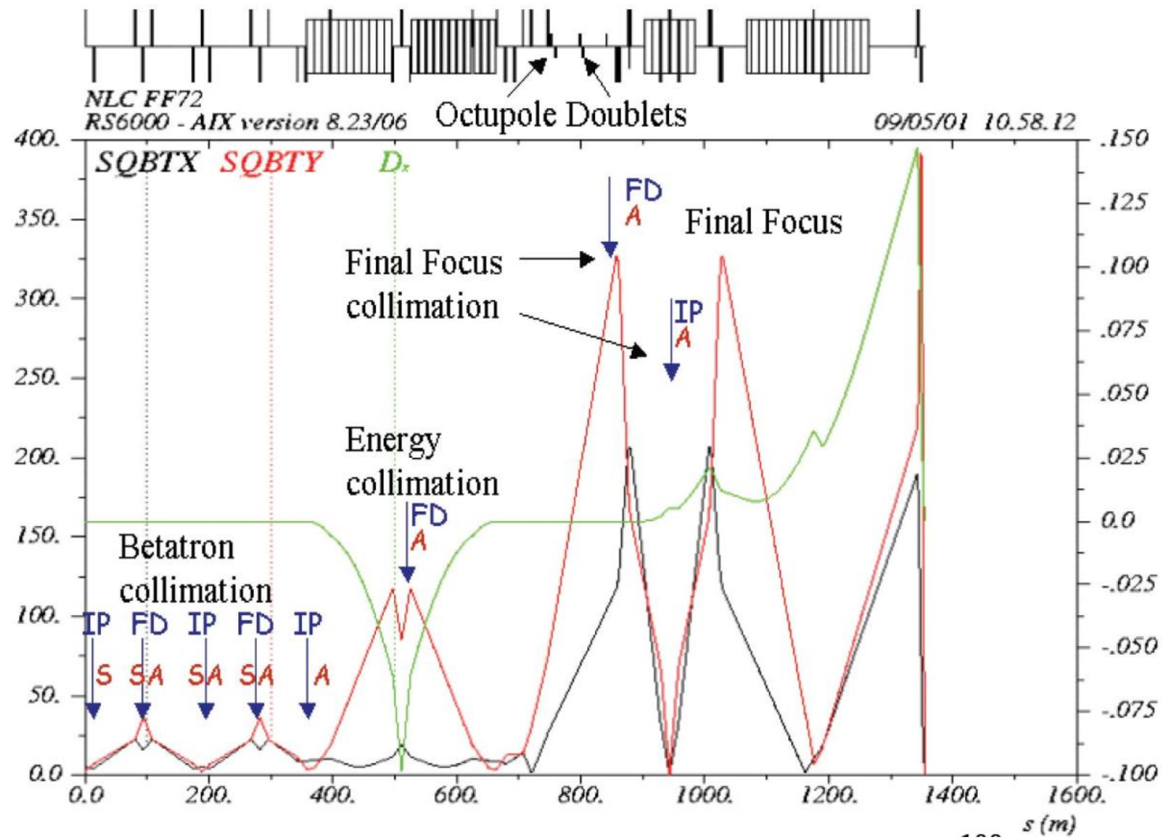


[N.Terunuma et al]

2x 11km s.c. linac

Example Linear Collider

Sqrt($\beta_{x,y}$)



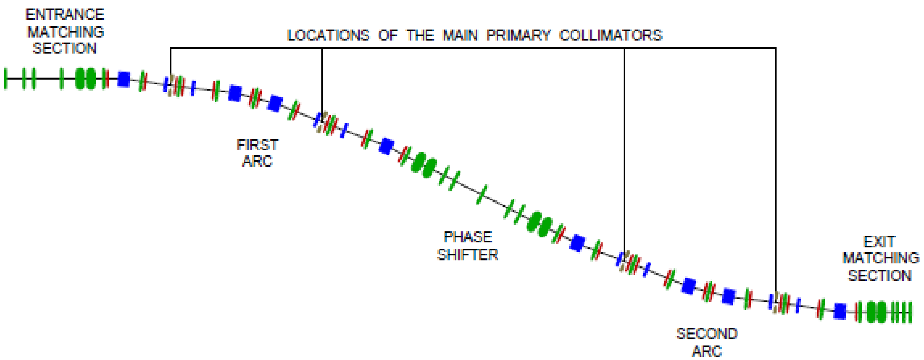
D_x [m]

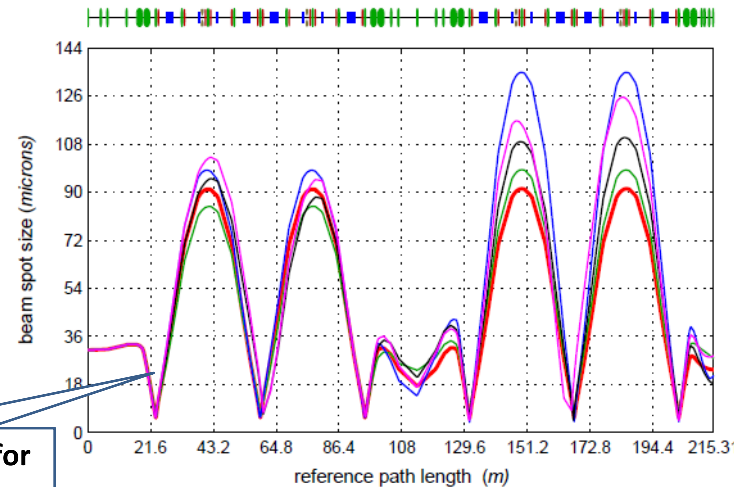
- Combination of chromatic/geometric aberration correction and collimation
- Small beam spot, high avg. Power
- Collimation to protect FF/detector

[A.Seryi et al]

Example Post Linac Collimation EXFEL

[V.Balandin, N.Golubeva et al]





Beam size, nominal and for off-energy, orbit offsets

- goal: protect permanent undulator magnets from halo losses; danger of de-magnetization; avoid accidental beam impact
- 4 primary collimators plus secondaries; beam size large enough for survival of accidental impact
- Second order achromatic properties to allow certain energy bandwidth

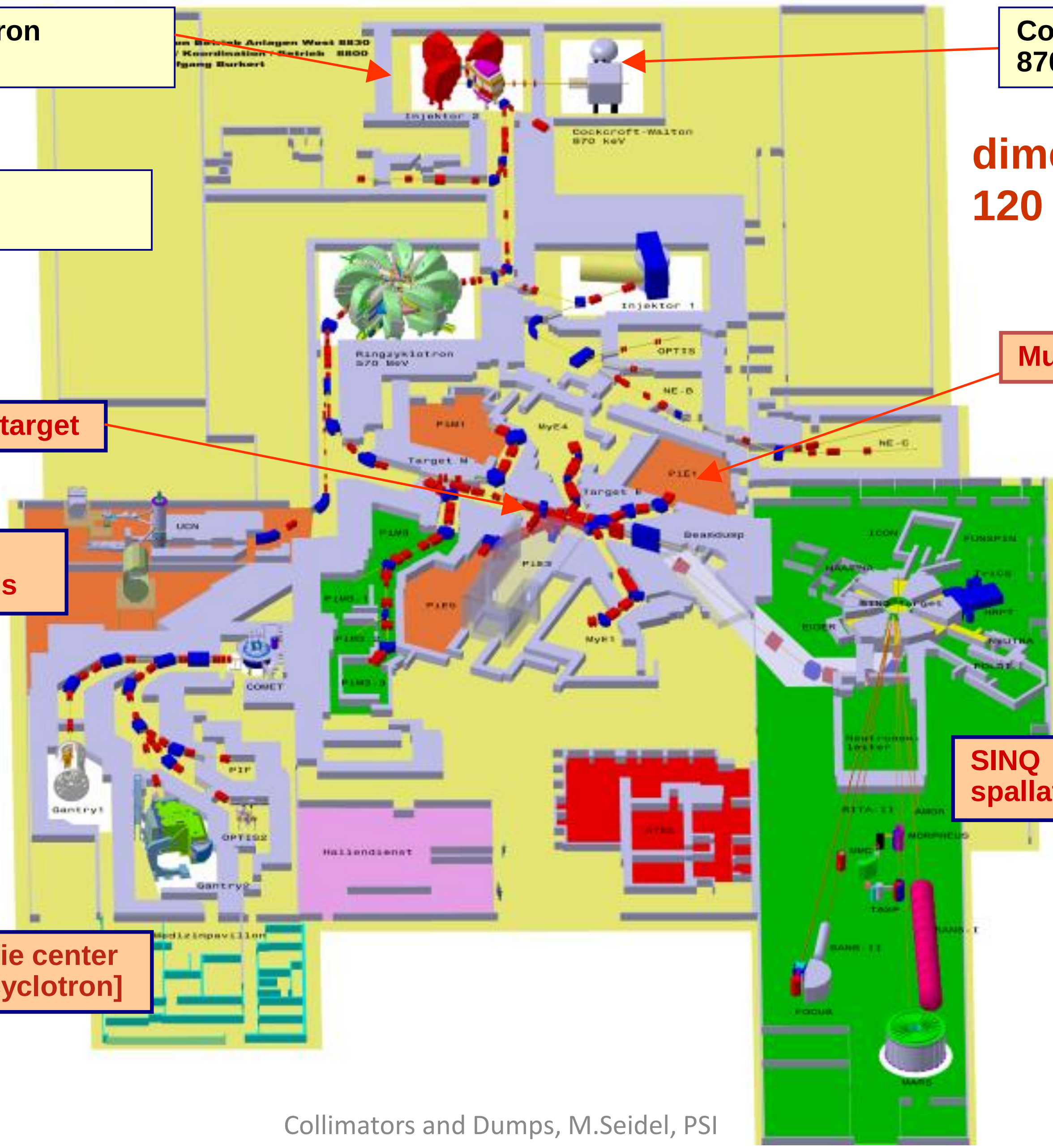
PSI- High Power Proton Accelerator

Injector II Cyclotron
72 MeV, 160kW

Cockcroft Walton
870keV, 10kW

Ring Cyclotron
590 MeV, 1.3MW

dimensions:
120 x 220m²



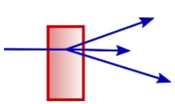
Muon Beamlines

4cm graphite target

UCN
Ultra-Cold Neutrons

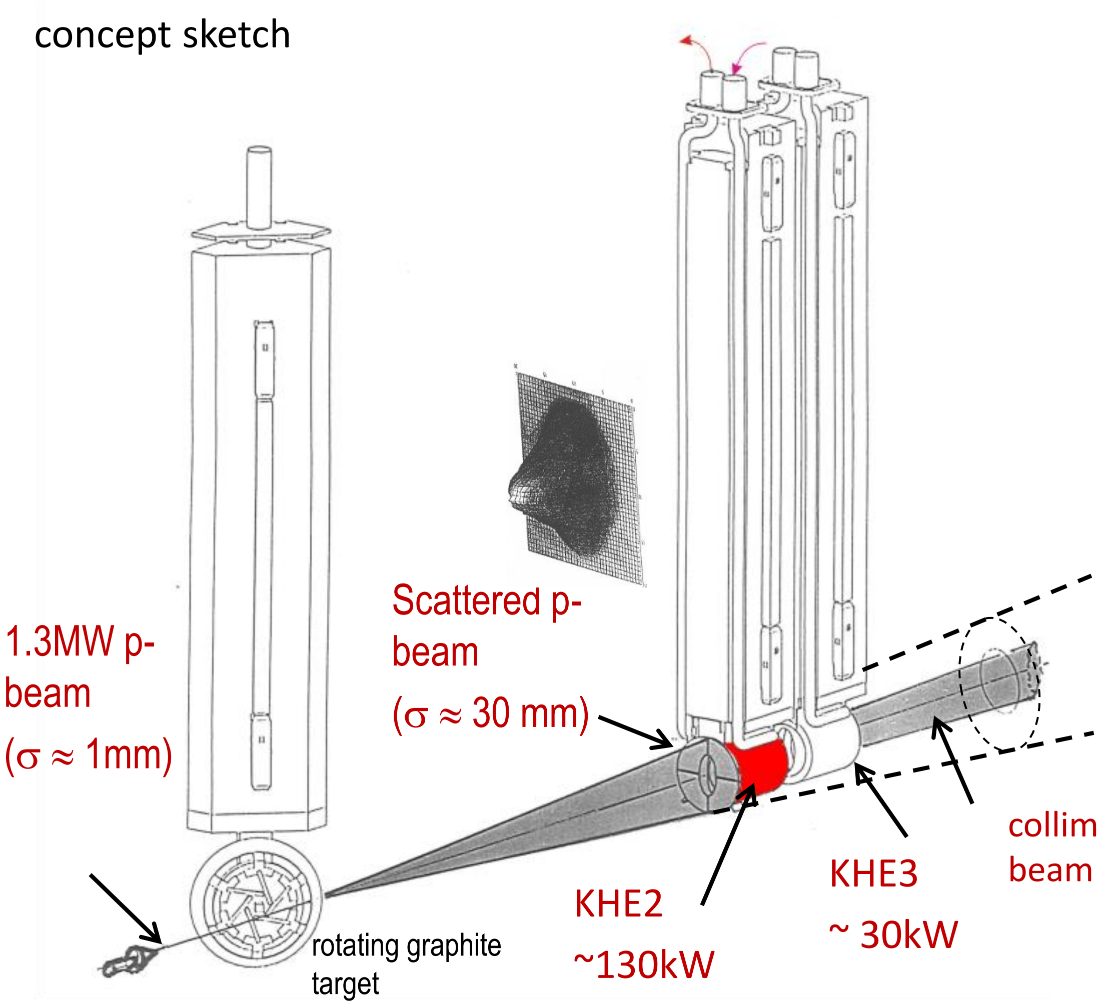
SINQ
spallation source

proton therapie center
[250MeV sc. cyclotron]

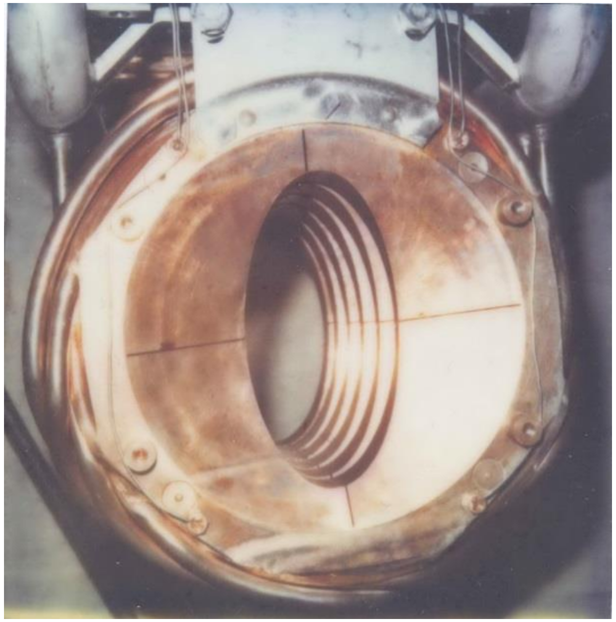


PSI-HIPA: high average load power

concept sketch



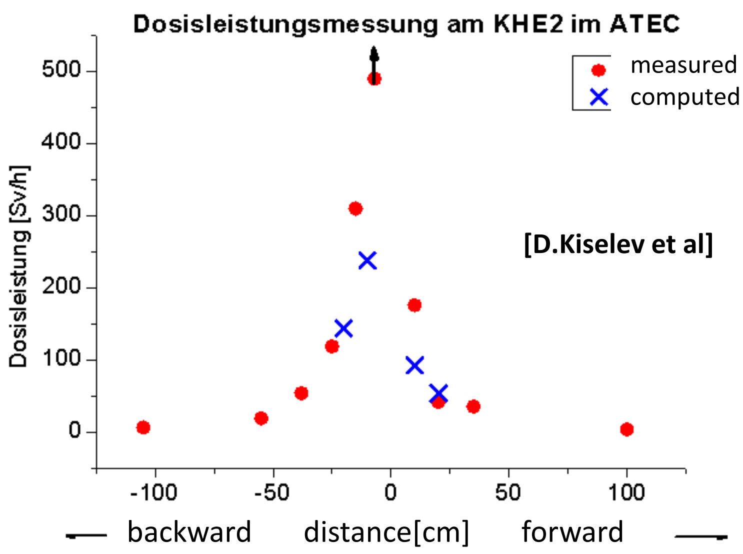
[D.Kiselev et al]

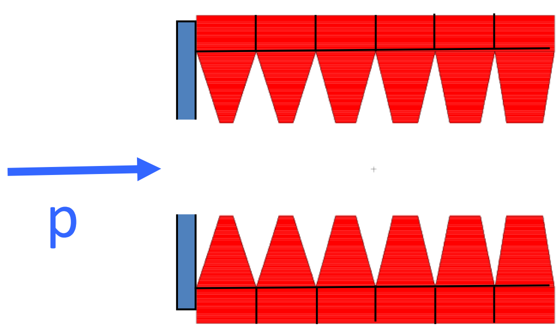


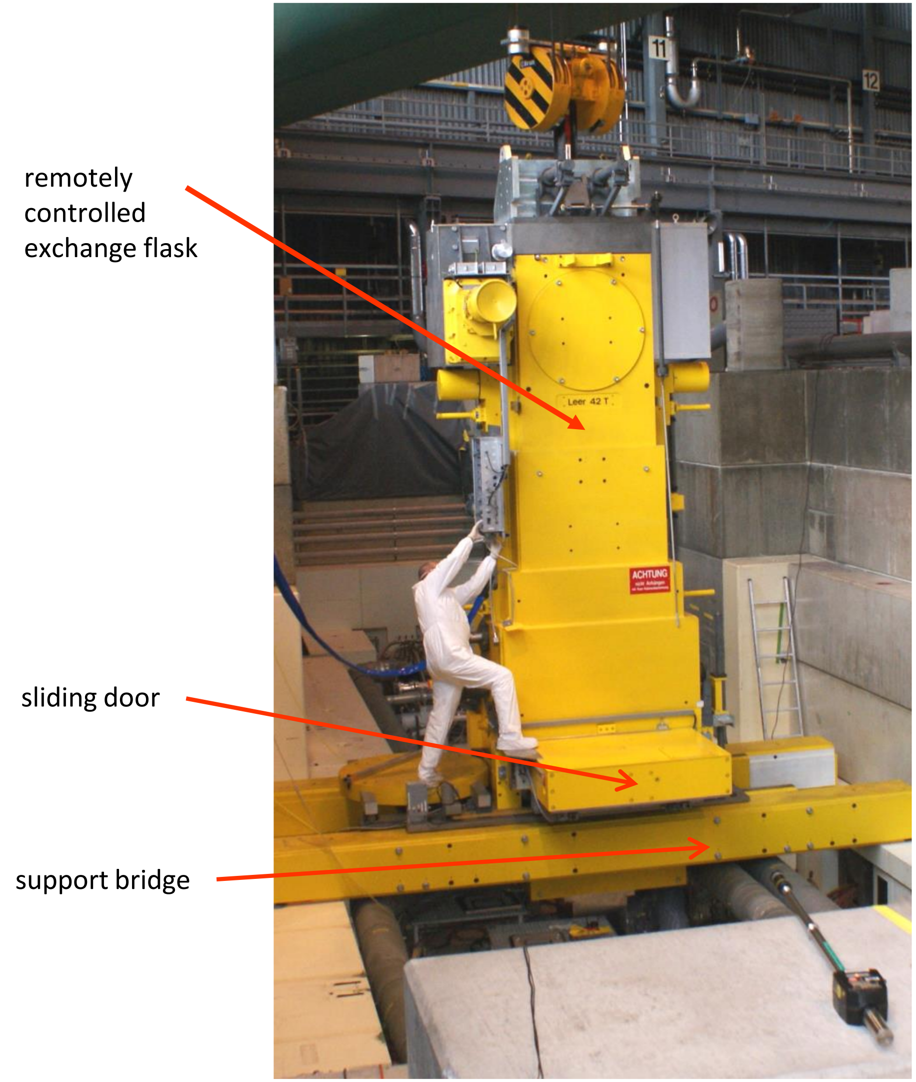
Aspects:

- Fixed aperture, no adjustments
- high power density → cooling
- protection of collimator
- high activation → shielding, handling

High intensity collimator: activation after years



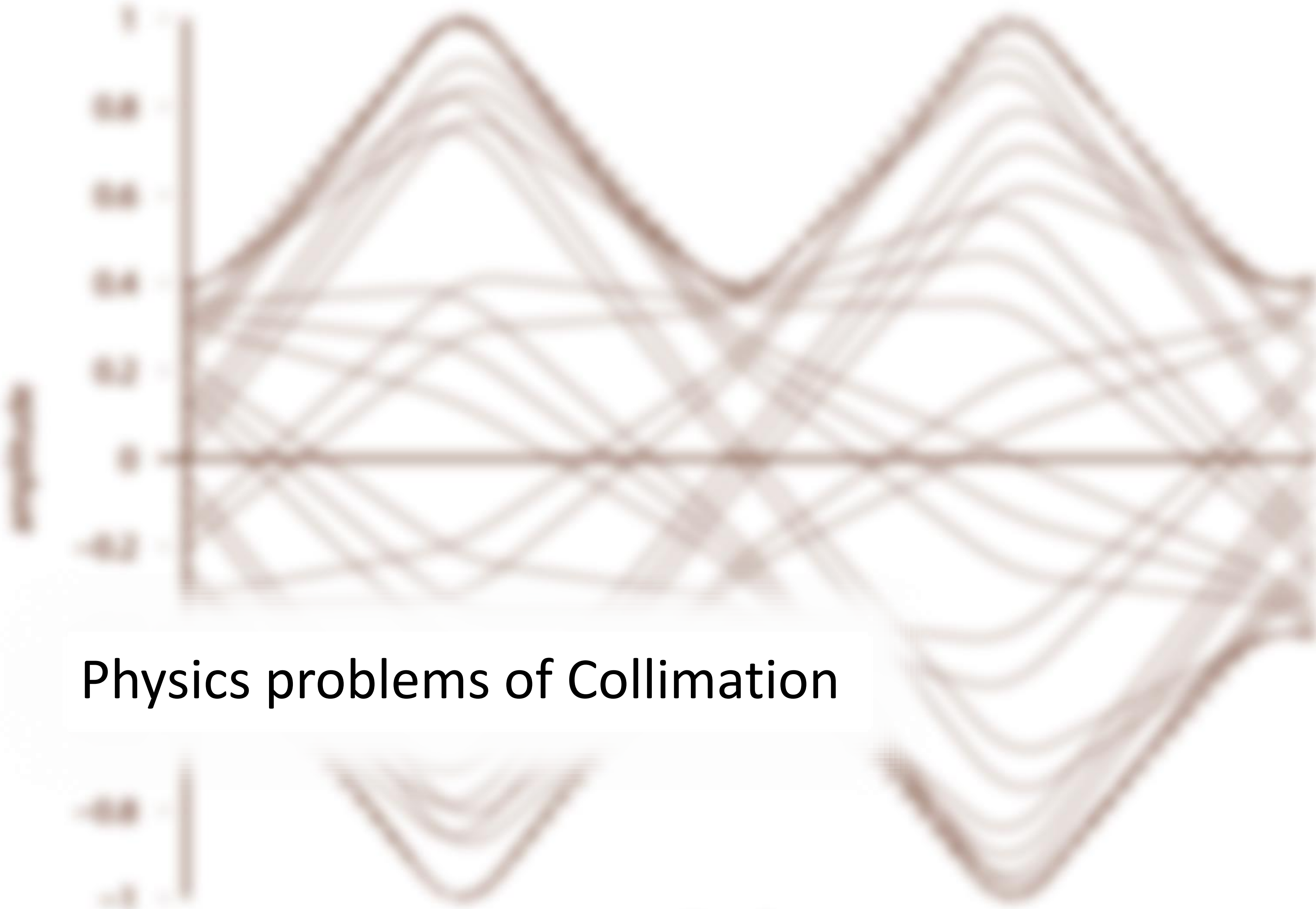




Energy, power and other impressive numbers

	storage rings		single pass		
	LHC	**FCC**	**ILC**	**EXFEL**	**PSI-HIPA**
beam kinetic energy	7 TeV	50TeV	up to 500GeV	17.5GeV	0.59GeV
beam stored energy / power	0.36GJ	8.4GJ	up to 13.7MW	0.65MW	1.4MW
tolerated beam loss power	0.5MW/10s	11MW (!)	low	low	130kW
rms beam size at collimator	200μm		200x15μm^2	100μm	≈ cm
comment	pioneering, impressive perf.	loss power is one of major issues		interchangeable apertures	after target, fixed aperture

→ **high energy/power** leads to tight requirements for **collimation efficiency**
→ … and demanding requirements for **thermomechanics** and interlock systems



Physics problems of Collimation

Collimation: a multi-physics problem

a) **Beam dynamics:** impact parameters (ring), collimation hierarchy, cleaning inefficiency, betatron phases, impedance/wake fields, tolerances …

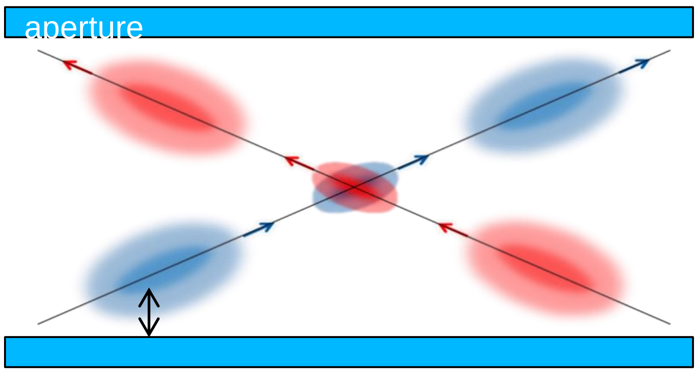
b) **Radiation transport**: phase space of scattered beam, energy deposition, activation

c) **Thermomechanical aspects**: shock- and continuous heating, thermal stress and resulting deformations, risk of fatigue failure, choice of material/advanced materials

d) **Operational aspects**: precision positioning, control through operation cycle, efficient positioning of large numbers of collimators, handling of activated components

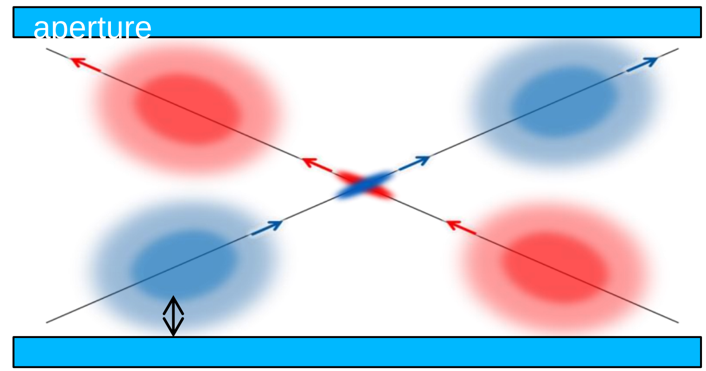
e) **Beam diagnostics**: monitoring of loss rate, temperatures, shock impact / damage, beam position at jaws

Collimation in rings – relation to β*



*Larger β**

Example:
LHC



*Smaller β**

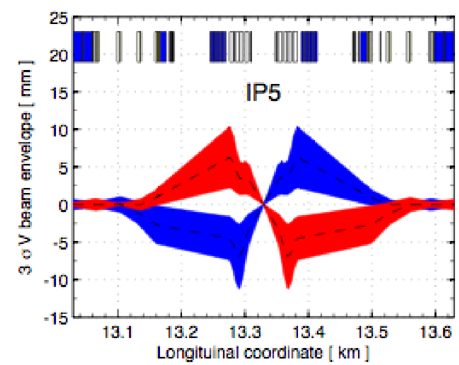
[R.Bruce, CERN]

- primary collimator typically at 5..7×rms width
- for highest luminosity the smallest possible β* is desired; the smaller β*, the larger the beam size in final focus quads

$$\beta(s) \approx \frac{s^2}{\beta^*}$$

- In units of beam rms-width collimators must be set tighter than the aperture of the beam

→ thus direct relation between β* and collimator settings



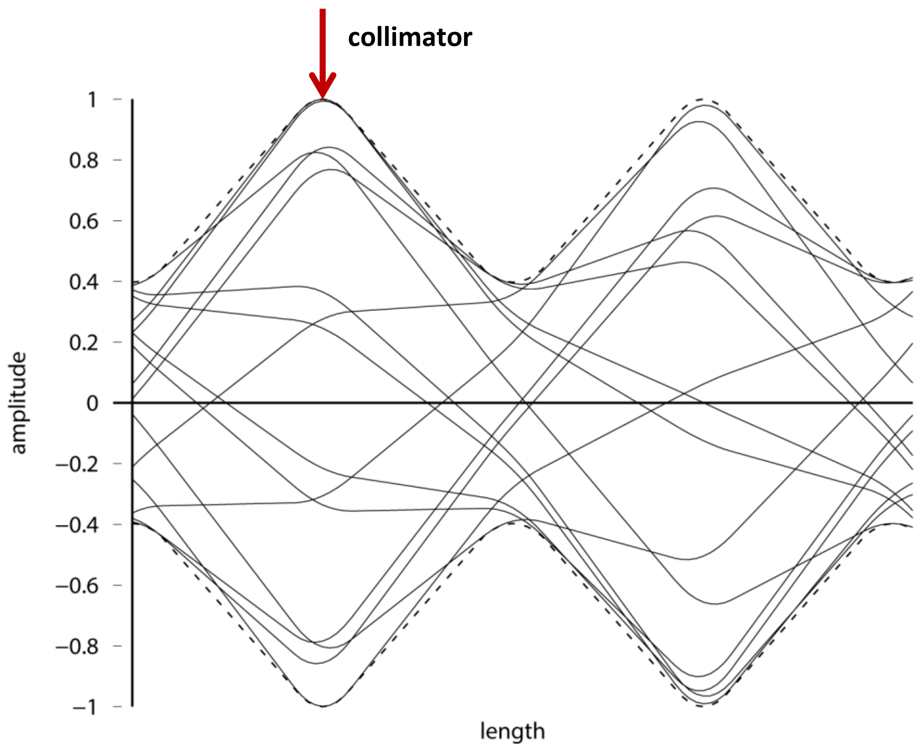
envelopes around IP

Betatron Collimation in Rings - Impact Parameter

Position a collimator at certain distance to the beam, e.g. 5 rms-width of core distribution.

I) At which distance from edge will the collimator be hit by particles?

II) Most particles will be scattered after first contact (angular kick, some energy loss). How can these scattered particles be captured?

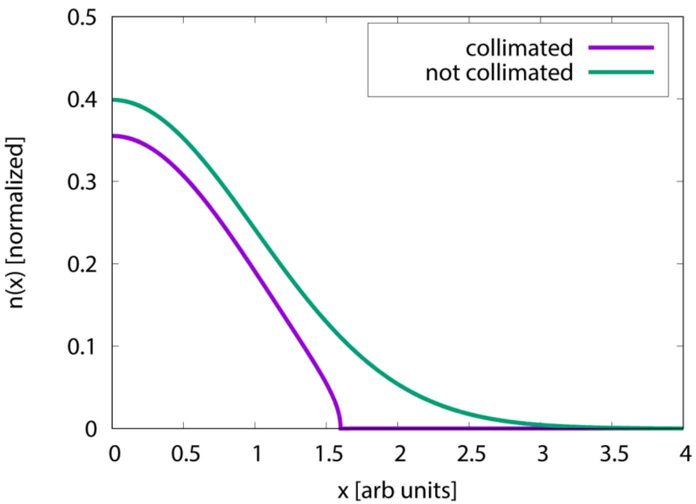


Betatron oscillations in a FODO lattice.

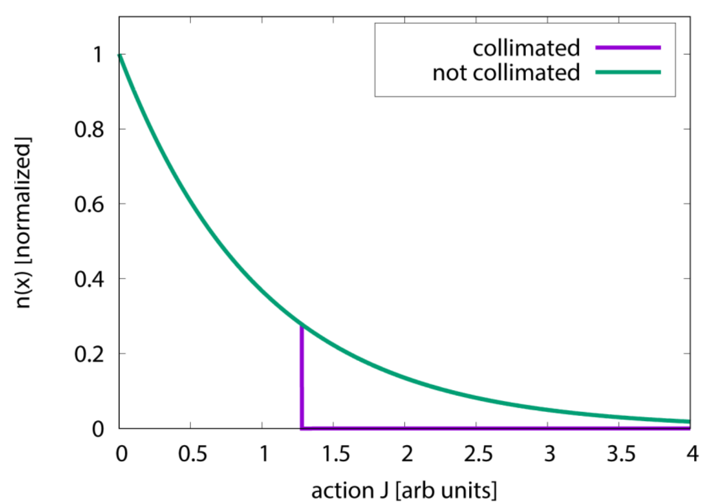
A particle that just passes the collimator will perform many turns before it finally hits the collimator at close distance from the edge.

To consider collimation in a hadron ring, use the distribution in action J

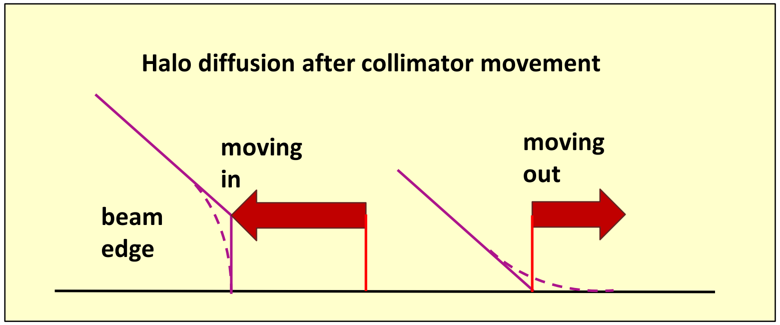
proj. distribution in x: Gaussian



distribution in J: Exponential



$$J = \frac{1}{2}\left(\gamma x^2 + 2\alpha x x' + \beta x'^2\right)$$



Determining diffusion in *J* by collimator retraction tests

$$\dot{n} \propto \frac{\Delta J}{\sqrt{Dt}}$$

$$\dot{n} \propto \left(1 - \mathrm{erf}\left(\frac{\Delta J}{2\sqrt{Dt}}\right)\right)$$

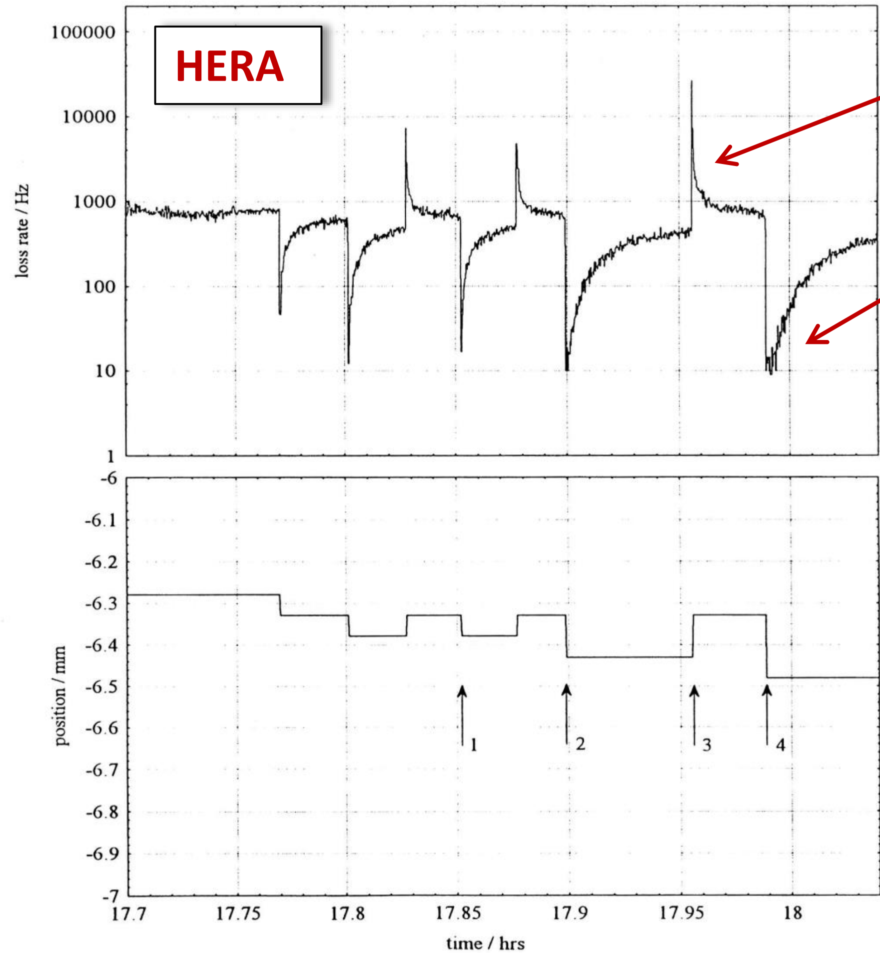
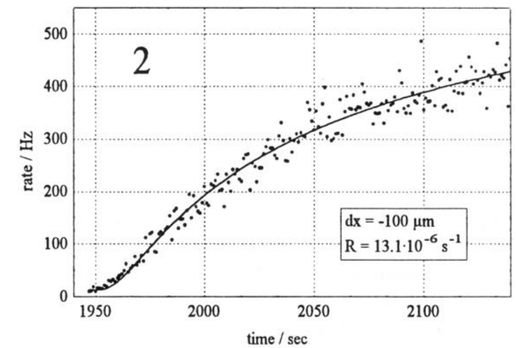
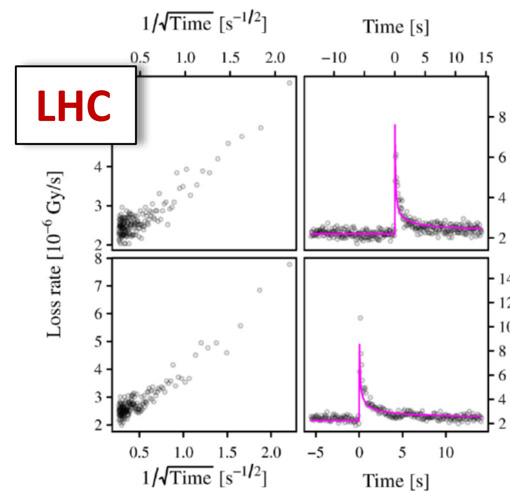


Fig. 5.5: Observed shower rates during collimator movements (upper plot). The jaw position is given on the lower plot. The time marks correspond to the following collimator movements:
1.) Δx = - 50 µm; **2.)** Δx = - 100 µm; **3.)** Δx = +100 µm; **4.)** Δx = -150 µm

NIM A 351, 279 (1994)





Valentino et al

(a)Inward collimator jaw movement

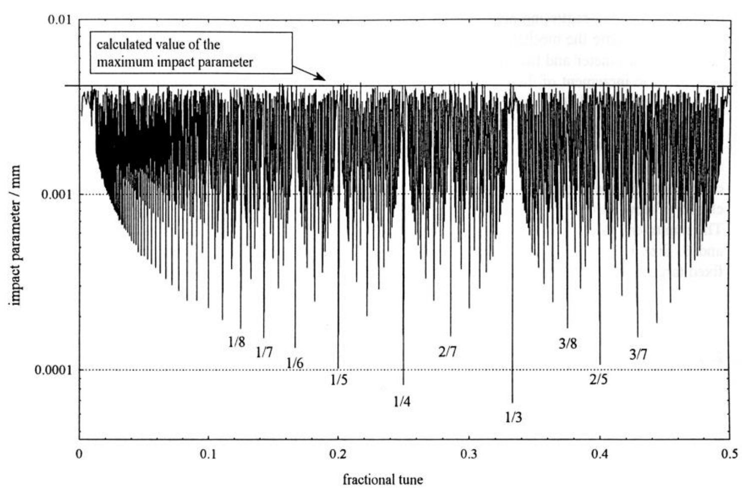
Halo Diffusion and Impact Parameters

The impact parameter (distance from edge) will be affected by:

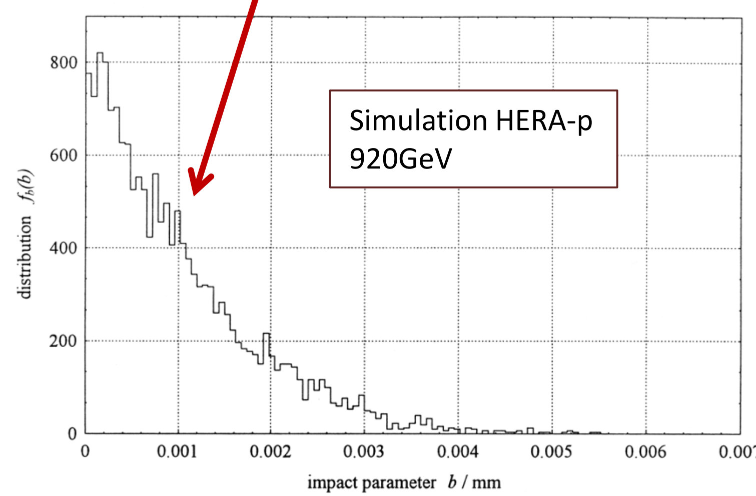
- Choice of betatron tune
- Nature of amplitude growth (e.g. characterized by diffusion coefficient)
- Slow oscillation mechanisms: betatron coupling, synchrotron oscillations

[for detailed considerations see **COLLI_HERA**]

1µm impact parameter is a typical value => small!



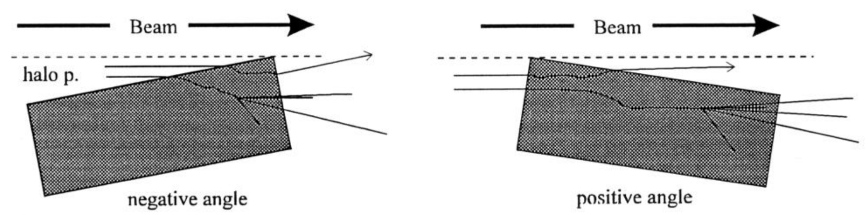
simplified linear growth:
away from resonant tunes the maximum impact parameter approaches a „typical“ value

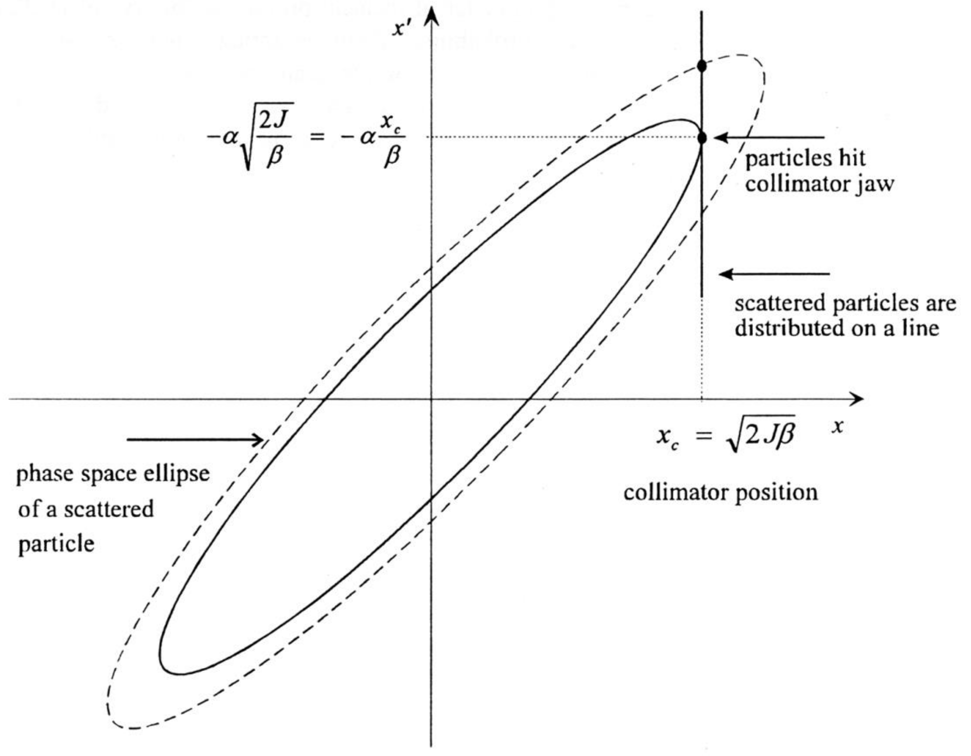


more realistic diffusion growth:
numerical simulation including slow oscillations

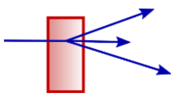
Scattering at Primary Collimator

→most particles will be scattered due to misalignment best possible alignment and flatness help to maximize the travel length in material and the scattering angle





1) In a ring, other than in a linac, due to the small impact parameter scattering always leads to an increase in action (secondaries can stay in shadow)
2) In general ($\alpha \neq 0$) alignment angle of jaw depends on amplitude

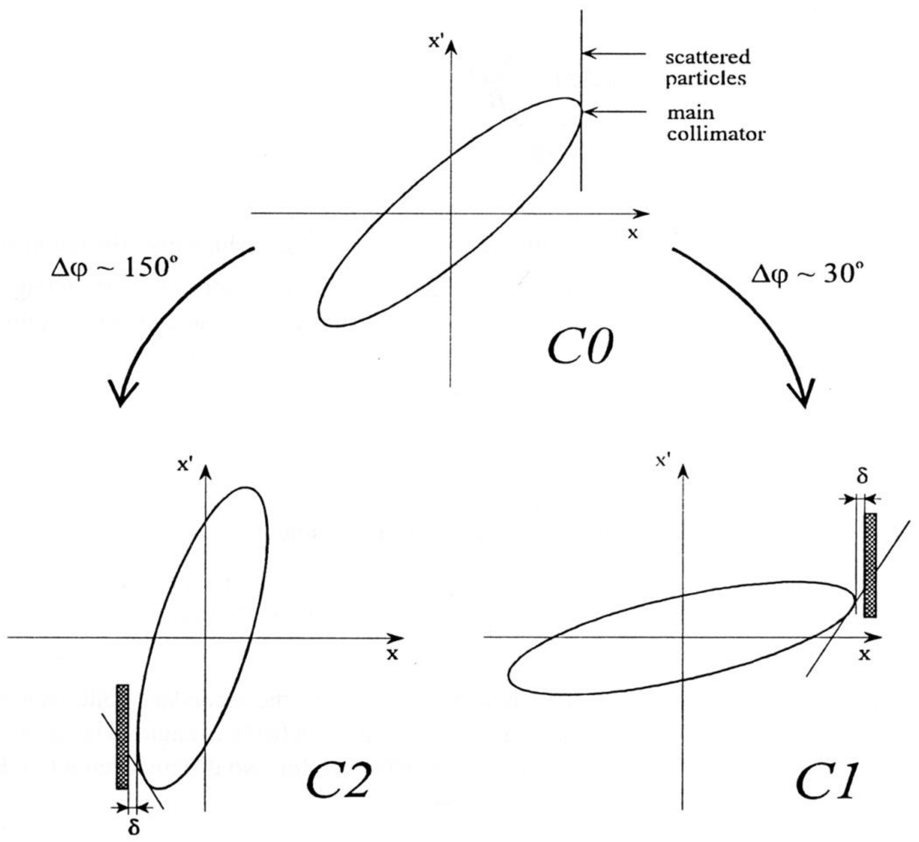


Two Stage Collimation

Scattered particles from the primary are absorbed at two **secondary collimators**; also tertiary collimators are possible

Optimum phase advances are around 30 and 150 degree

Secondaries should stay **in the shadow of primaries** (tolerances!), while the natural aperture should stay in the shadow of all collimators



Momentum Collimation

- install collimators at positions with large dispersion function
- always a combination of transverse and longitudinal amplitude

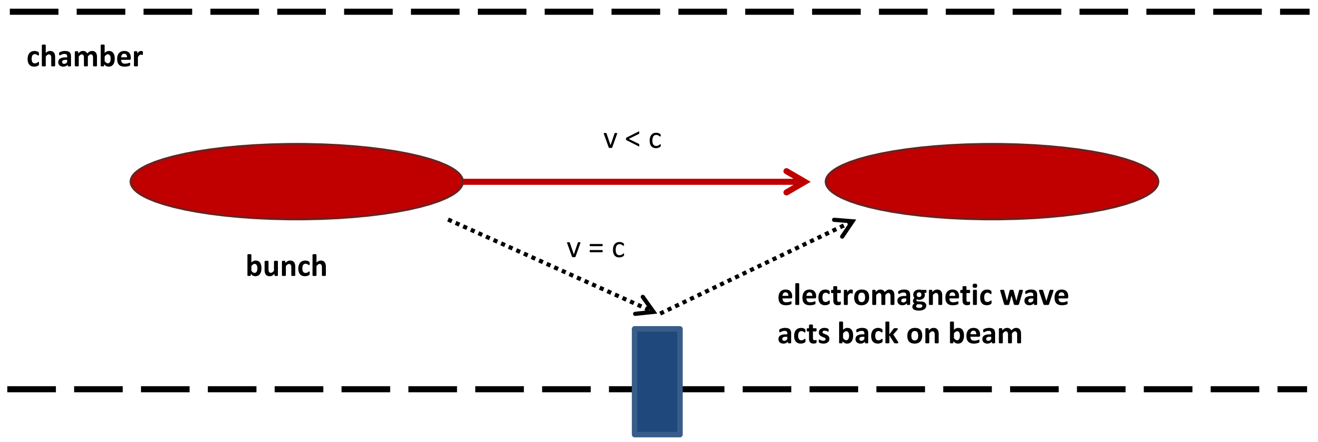
$$x(s) = \sqrt{2J_x\beta_x(s)}\cos(\varphi(s) - \varphi_0) + D_x(s) \times \frac{\Delta p}{p}$$

Betatron part

Momentum part
choose location with large D_x for momentum primary collimator

- Collimator hierarchy is still o.k. if: $\frac{|D_p|}{\sqrt{\beta_p}} \geq \frac{|D_s|}{\sqrt{\beta_s}}$
  (p-primary, s-secondary)

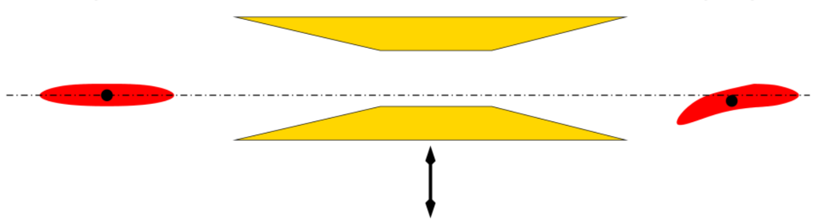
Collimator Wakefields



- collimator material positioned close to beam
- **geometric** and **resistive wakefields** act back on the beam
- in Ring: contribute to Impedance (multi bunch/turn), onset of instabilities
- in Linac: kick acts back on beam, disturbs beam shape, increases energy spread

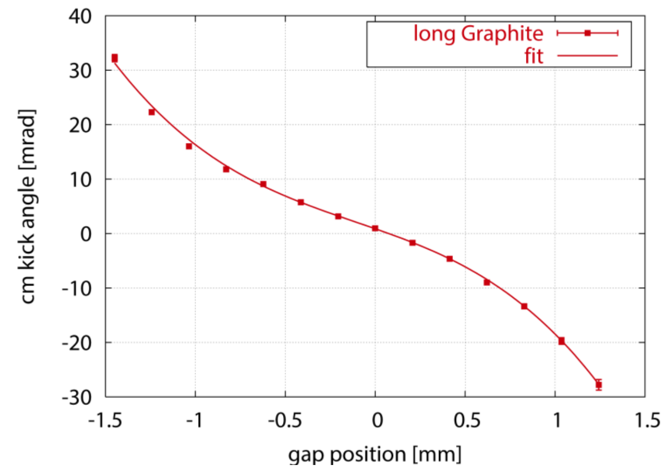
Example: geometric and resistive wakefields measured in SLAC Linac

Method: high quality electron beam passes collimator gap at varying position, determine angular kick from difference orbits; done for copper and graphite



graphite jaws

Parameters: gap=3.8mm, σ_y=50µm, 1.2GeV



result for graphite jaw: $w_\perp$ = 3±0.3 V/pC/mm
or in practical units: θ = 8.2±0.7 µrad/mm
→ agrees to theory within 20%

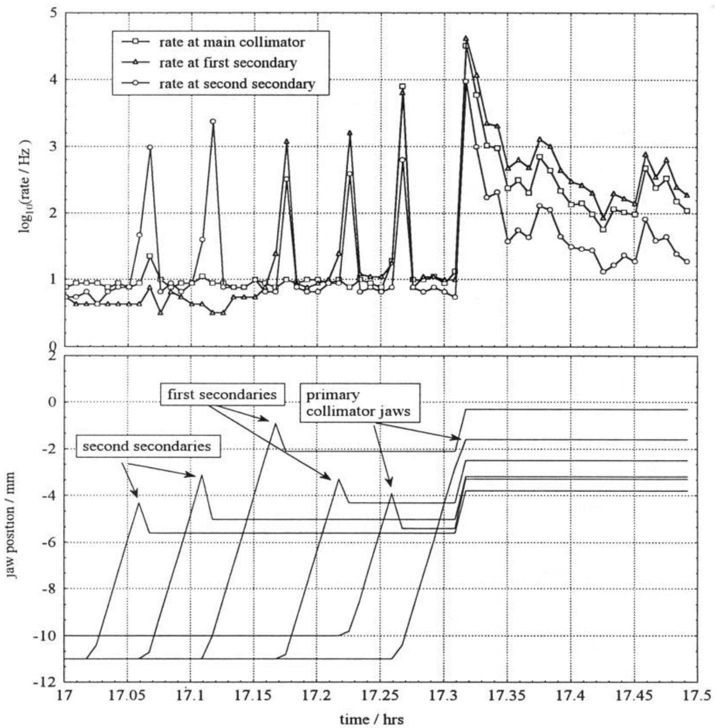
[WAKE]

Operational Aspects

Positioning of collimators close to the beam is critical!

serious cutting into the beam would result in excessive loss, unwanted beam dump, even jaw damage or quench → care needed!

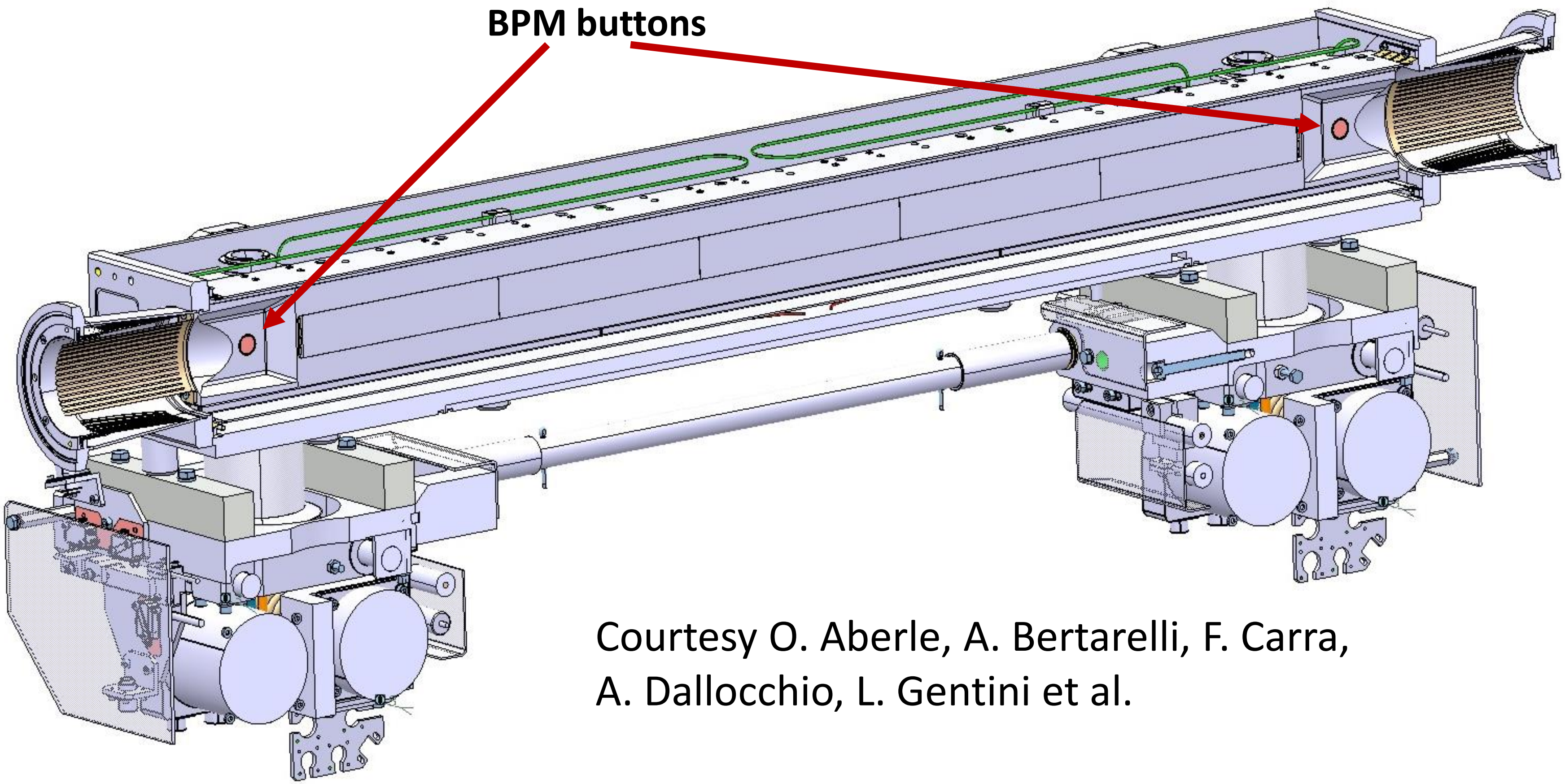
But - conservative probing of beam with many jaws costs much luminosity → automation, refinement, jaw BPMs



Example DESY-HERA, 1994

automatic alignment of two primaries (x,y) and 4 secondaries using loss rates and edge detection

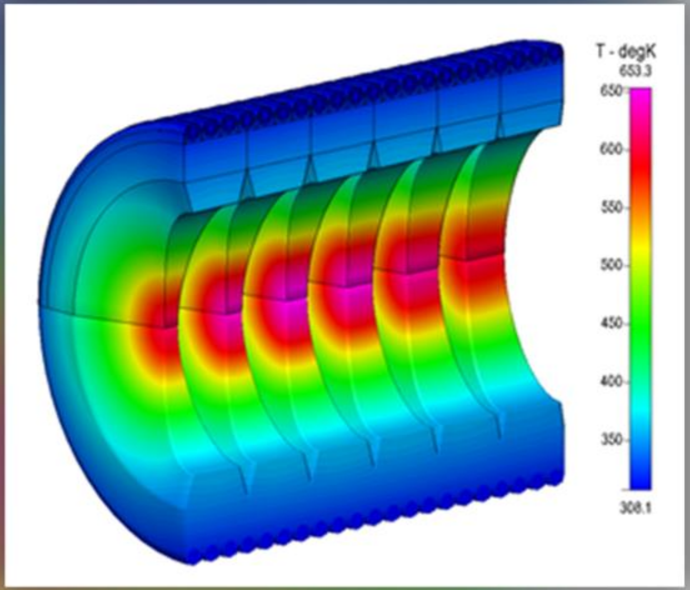
CERN: Jaws with integrated BPM´s



Courtesy O. Aberle, A. Bertarelli, F. Carra, A. Dallocchio, L. Gentini et al.

- drastically reduced setup time
- higher setup precision $\rightarrow$ tighter settings acceptable $\rightarrow$ smaller β^*

$\rightarrow$ Higher Luminosity



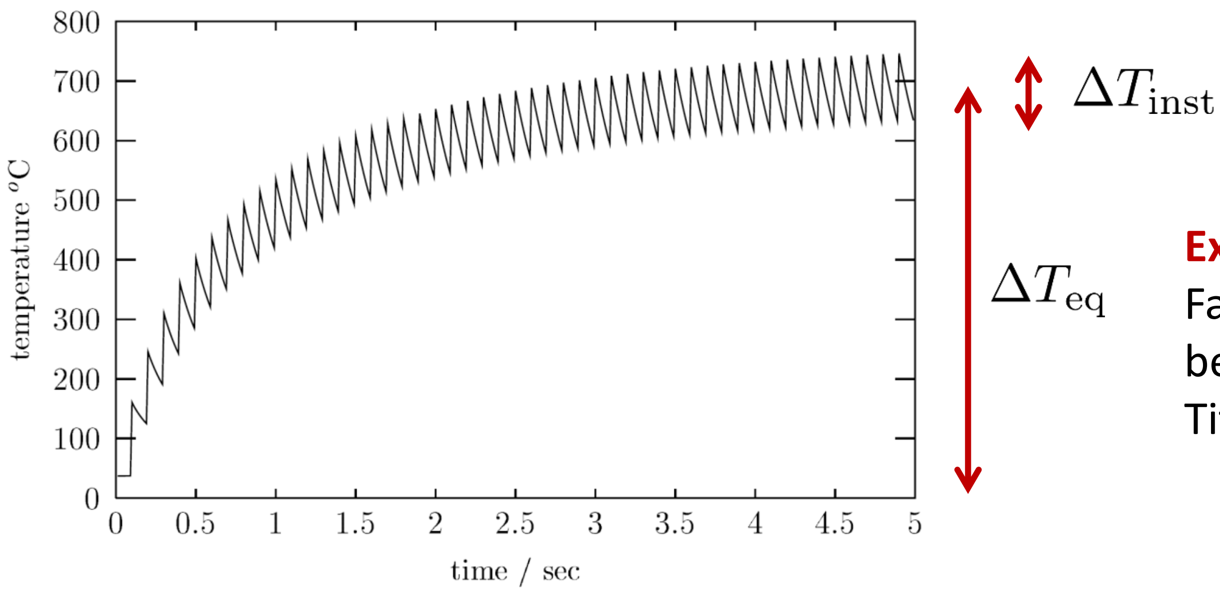
beam material interaction and heating for collimators and dumps

Collimators & Dumps: Thermomechanics

Beam deposits thermal energy

I) Instantaneous heating → shock, stress, fatigue failure?

II) Equilibrium heating → cooling, melting?



Example: TESLA Test Facility, 1.5mm electron beam, 800MeV, 10Hz, Titanium

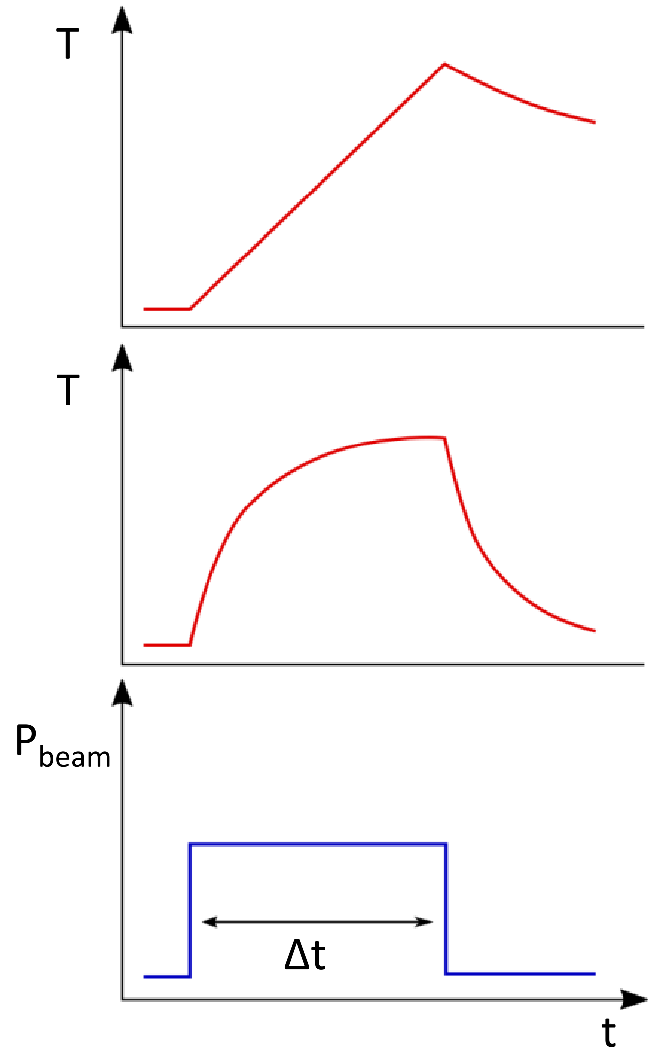
Instantantaneous vs. equilibrium heating

thermal diffusion coefficient relates time and length scales:

$$D_{\rm th} = \frac{\lambda}{c\rho} = \frac{\langle \Delta x^2 \rangle}{\Delta t}$$

$$\rightarrow \Delta x = \sqrt{D_{\rm th} \Delta t}$$

λ = th. conductance
c = heat capacity
ρ = density



$\Delta x \ll \sigma_{\rm beam}$

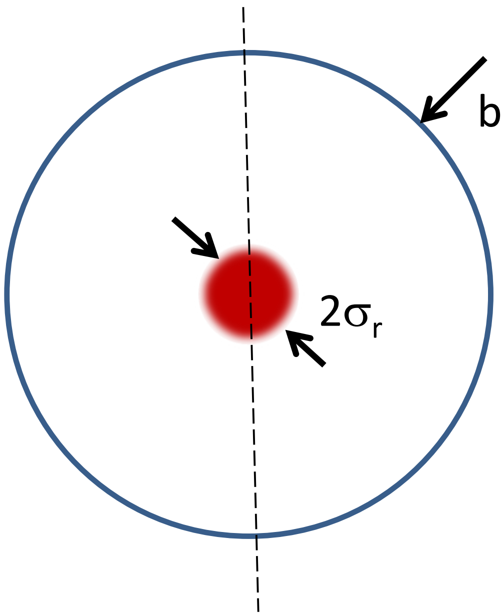
all energy is deposited in heat capacity of beam volume

$\Delta x \gg \sigma_{\rm beam}$

heating and conductance-cooling come to equilibrium

beam pulse heats material

Edge Cooling and Equilibrium Temperature



Solution also correct for half cylinder with half beam

Static heat diffusion equation for long cylinder

conductance — Source term ~ dE/dz — similar Gauss, integrable

$$\lambda \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} T(r) + q(r) = 0, \quad q(r) \propto \frac{2\sigma^2}{\pi(r^2+2\sigma^2)^2}$$

Temperature: logarithmic dependence on beamsize:

$$\Delta T_{\mathrm{eq}} \propto I_{\mathrm{beam}} \frac{1}{\lambda} \frac{dE}{dz} \ln\left(\frac{b}{\sigma}\right)$$

th.expansion, elastic modulus — yield strength

mechanical stress:

$$\sigma_{\mathrm{eq}} \approx \frac{1}{2} \alpha E \Delta T_{\mathrm{eq}} < \sigma_{0.2}$$

radial fixed plate, neglecting dynamic effects [Sievers, see Appendix]

Summary on continuous heating:

- weak dependence on beam size (logarithmic)
- relevant material parameters:

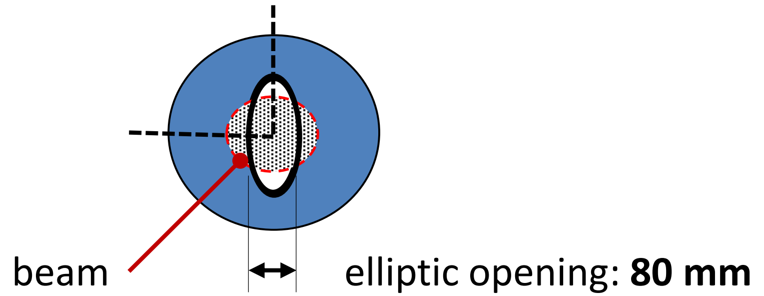
  $dE/dz\downarrow$, $\lambda\uparrow$, $T_{melt}\uparrow$, $\alpha\downarrow$, $E\downarrow$, $\sigma_{0.2}\uparrow$

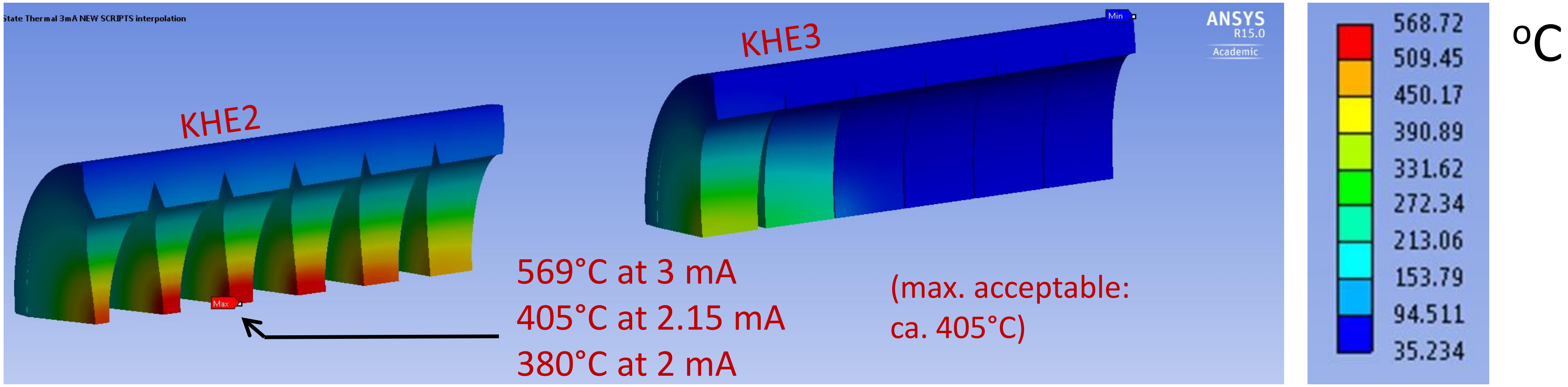
[HEAT, STRESS]

Numerical Calculations

use finite element codes like ANSYS, COMSOL to solve diffusion equation, extend to stress calculations → most accurate method, but less understanding of the nature of problem …

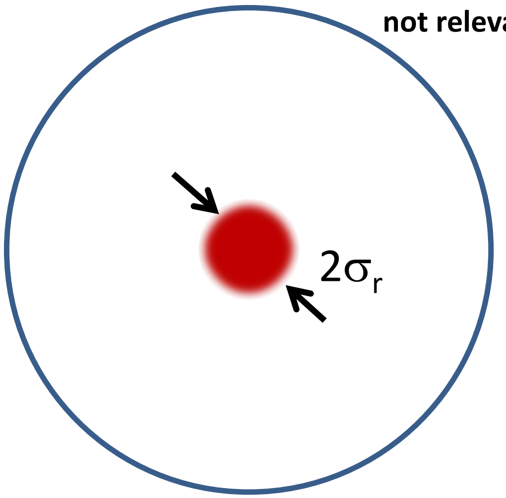
Example: PSI-HIPA: collimator II, III behind target





Instantaneous Heating

cold boundary, radius not relevant



core expands, circumference not
→ mechanical stress

heat capacity

$$\Delta T_{\mathrm{inst}} \propto \frac{Q_{\mathrm{train}}}{\sigma_r^2} \frac{1}{c} \frac{dE}{dz}$$

quadratic dependence on beam size

→ stress may have dynamic peaks from superposition of shock waves or resonances, otherwise **same as for equilibrium case**
→ particularly problematic: cavitation shock waves in liquids, e.g. Mercury

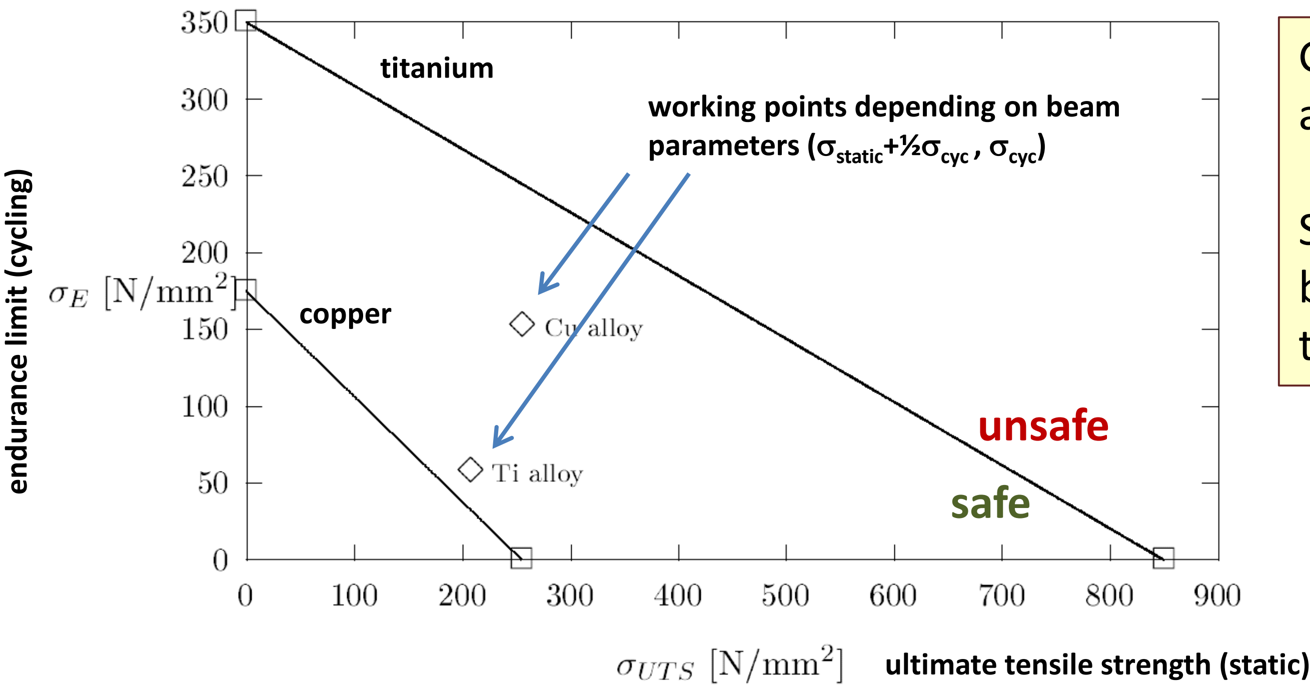
Summary instantaneous heating:

- Strong dependence on beam size (quadratic)
- Relevant material parameters:

  $dE/dz\downarrow$, $c\uparrow$, $\alpha\downarrow$, $E\downarrow$, $\sigma_{0.2}\uparrow$

combining instantaneous and equilibrium heating

Often operation requires intermediate regime with average and superimposed pulsed heating; e.g. at elevated temperatures material strength is reduced



Goodman diagram after D.Walz/SLAC

Stress limits are to be taken at elevated temperatures

→ Ultimately a simulation code, ANSYS or similar, should be used to obtain precise results. However, the presented analytical approaches allow rough estimates and qualitative understanding.

Estimating energy loss for protons and ions

Is all delivered by simulation codes, for estimates use
Minimum of Bethe-Bloch Formula:

material	$(dE/dx)_{min}$ [MeV/cm]	$(dE/dx)_{min}/\rho$ [MeV cm^2/g]	ρ [g/cm^3]
C	3.8	1.74	2.2
Cu	12.5	1.40	8.96
W	22.2	1.15	19.3

Often just normalized
value tabulated

rms scattering angle: $$\theta_{\mathrm{rms}} \approx \frac{13.6\mathrm{MeV}}{\beta cp} z \sqrt{\frac{\Delta x}{X_0}}$$

→ for electron induced losses include Bremsstrahlung (Berger-Seltzer formula)

Copper Carbon-Diamond (CuCD)

Crystal Channeling

Molybdenum Coating

HOLLOW ELECTRON BEAM COLLIMATION

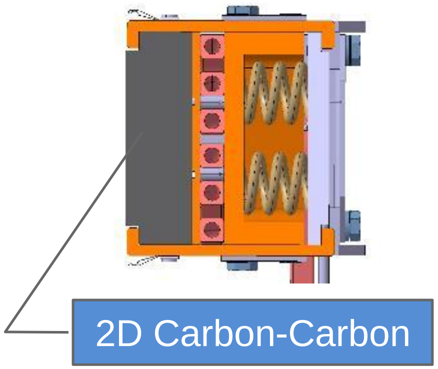
Molybdenum Graphite Composite (MoGr)

Next: advanced collimation

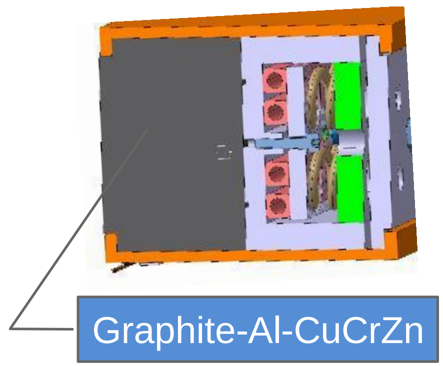
LHC collimators: advanced designs utilizing specialized materials

- Materials of the **jaws** are the **critical component** because of the tough requirements (**robustness**, **geometrical stability**, **electrical conductivity**, **radiation resistance** ...)
- **New advanced materials** being investigated for HL-LHC

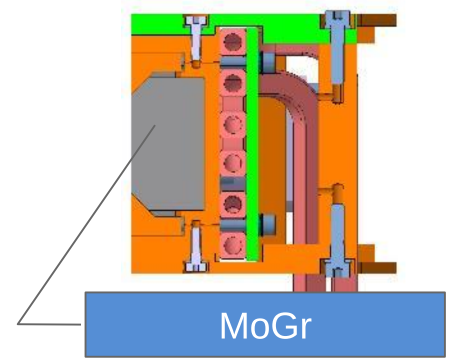
TCPP /TCSP (LHC and HL-LHC)



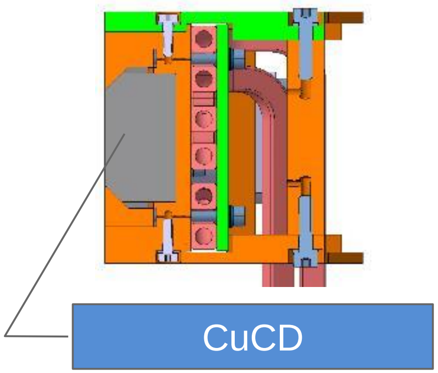
TDIS (HL-LHC)



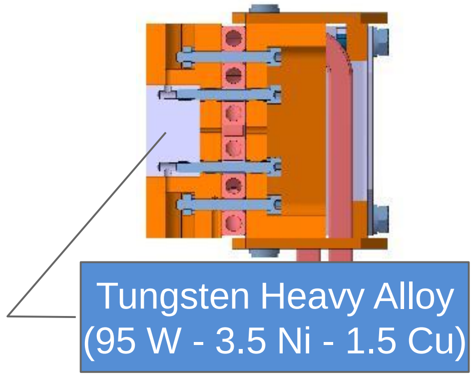
TCSPM (HL-HLC)



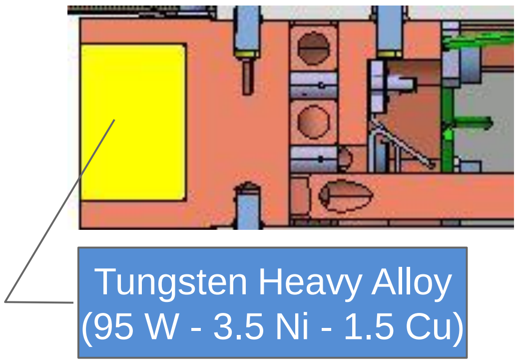
TCTPM (HL-HLC)



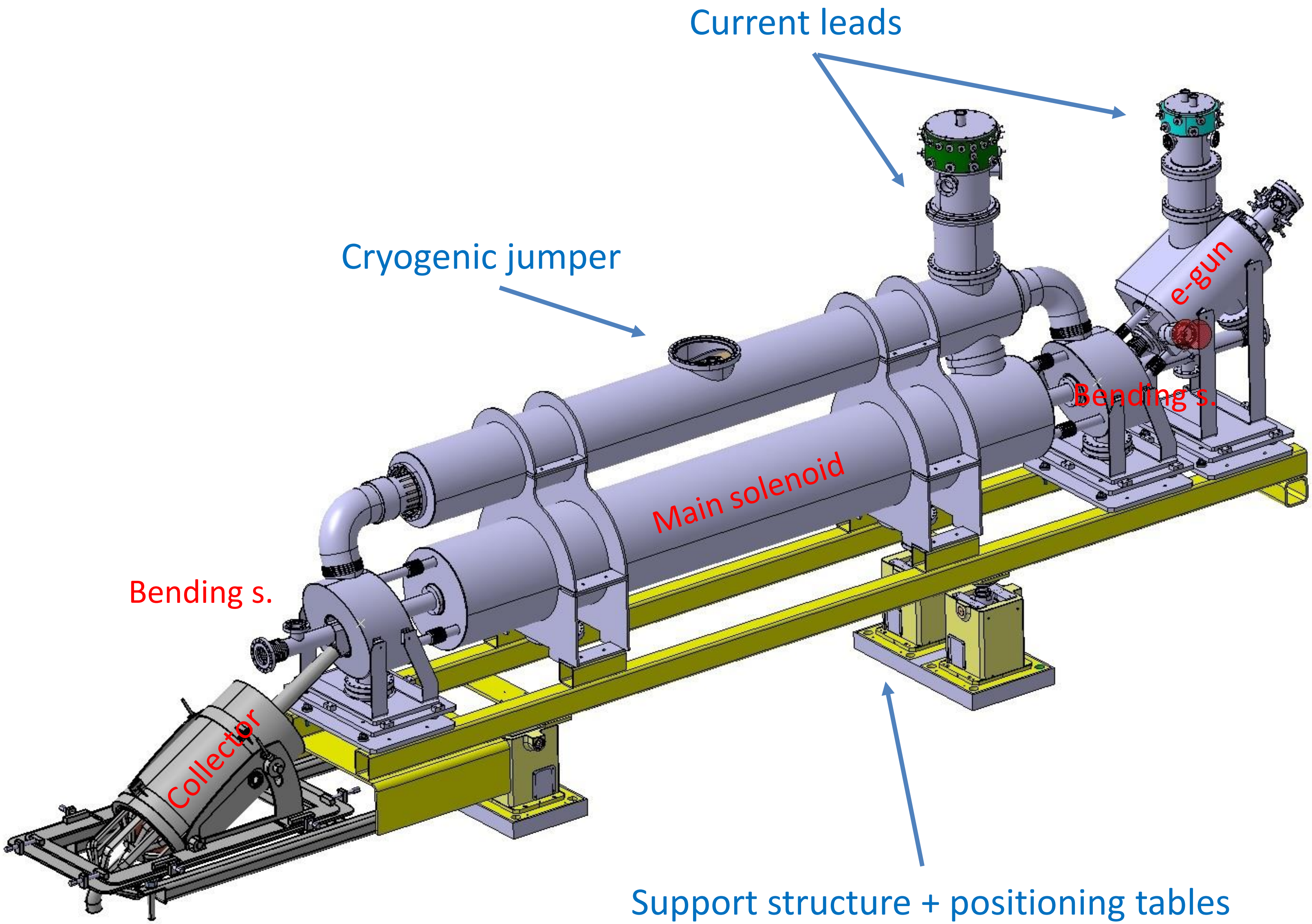
TCTP (LHC and HL-LHC)



TCLD (LHC and HL-LHC)

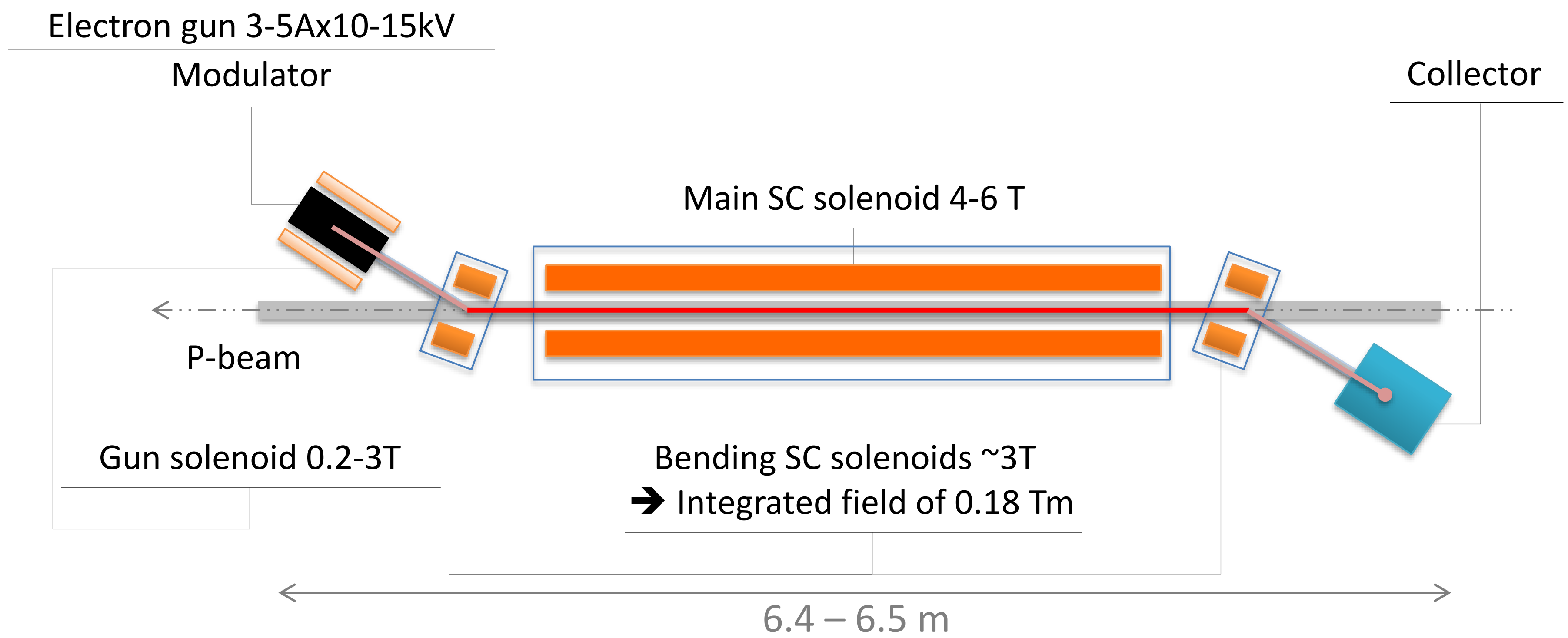


Hollow Electron Beam Lens for LHC



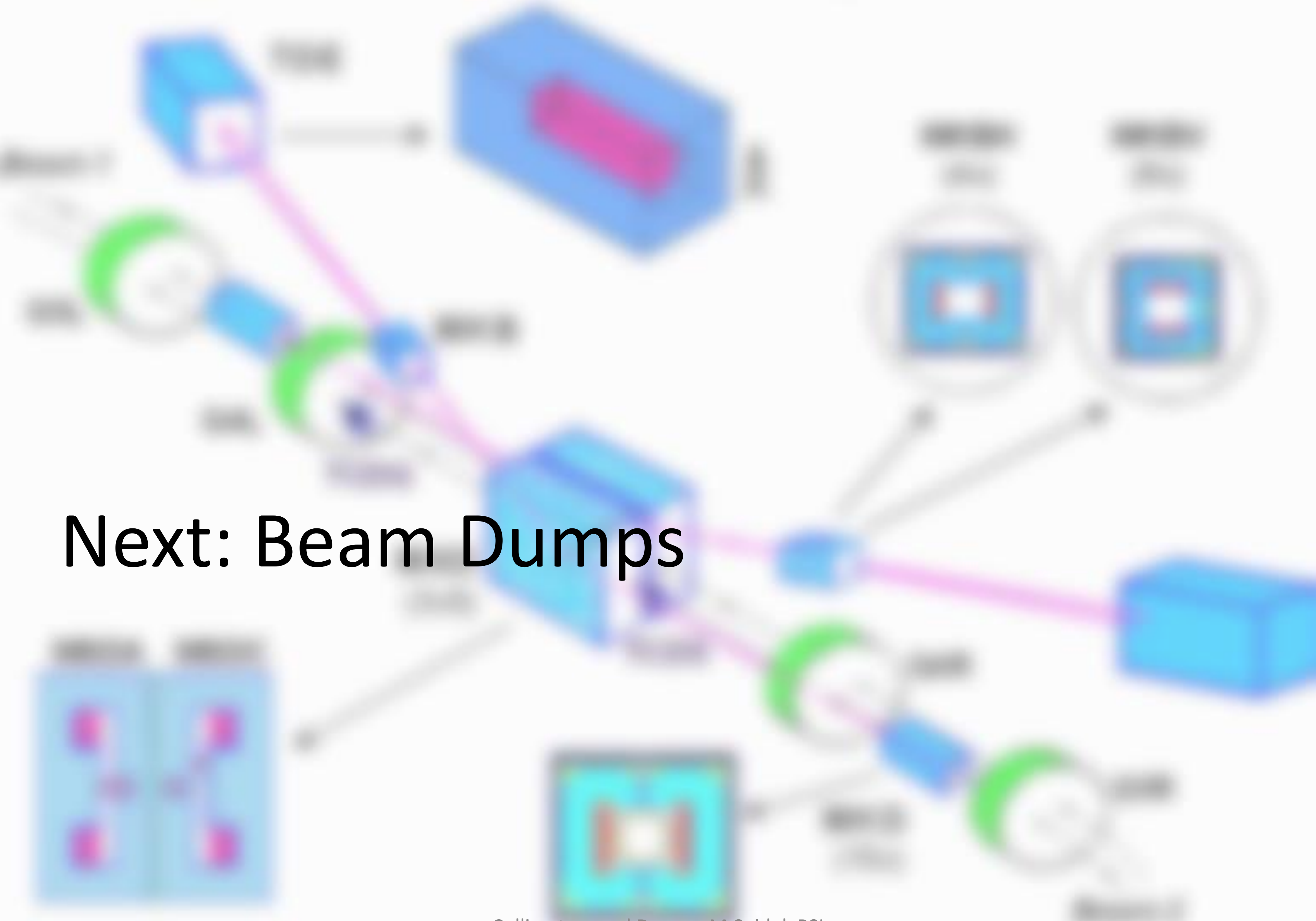
[O. Brüning, Diego Perini et al, Chamonix Performance Workshop 2018]

Hollow Electron Beam Lens - Concept



[A. Rossi et al, HL-LHC annual meeting 2017 in Madrid]

Next: Beam Dumps



Beam Dumps

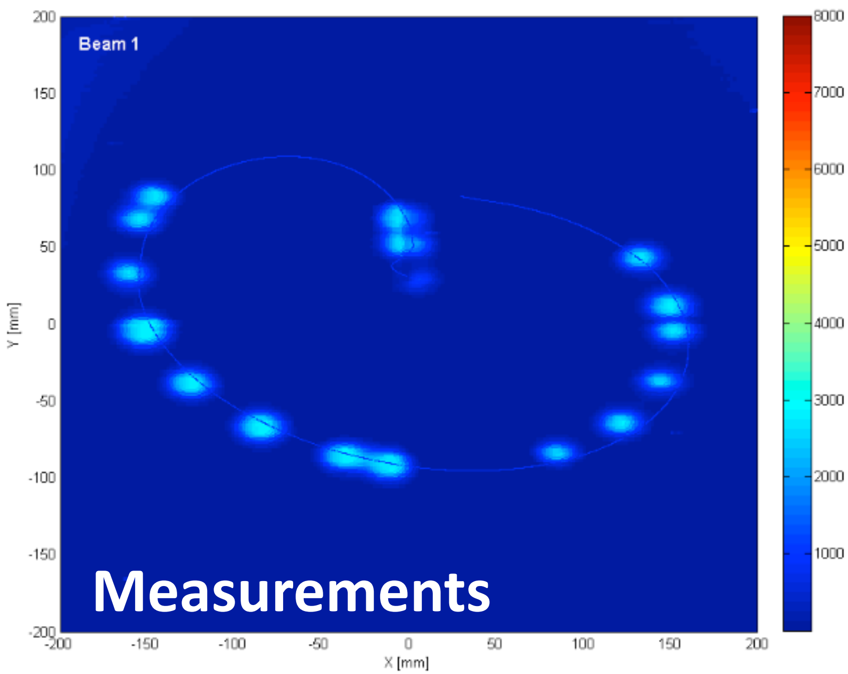
Purpose of beam dumps:

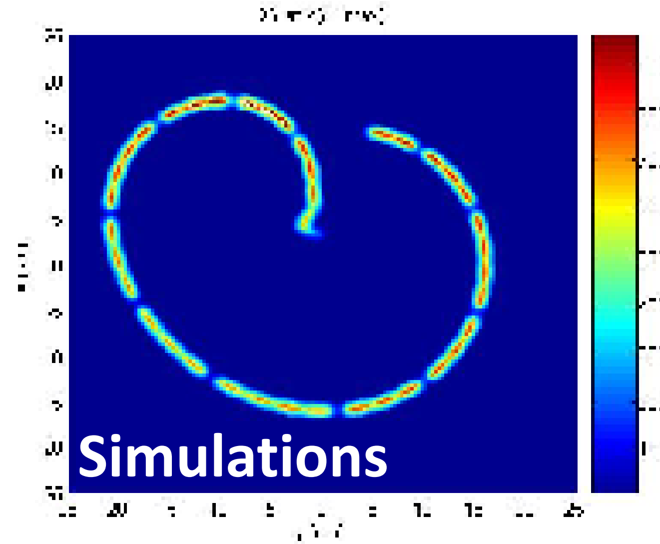
- Stop the beam safely within a defined volume
- Confine secondary activation

Challanges:

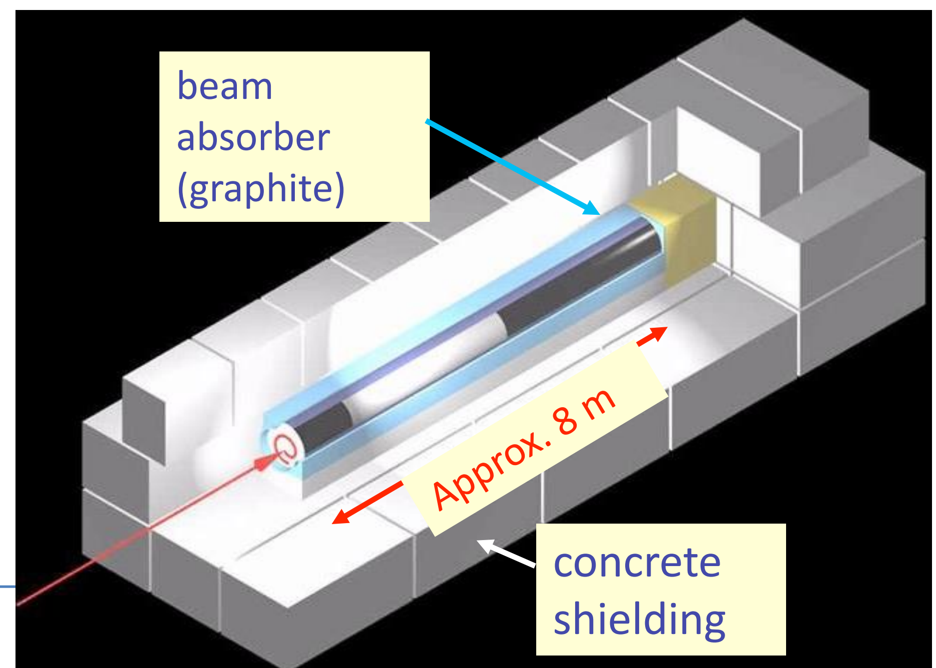
- Shock heating
- Average heat load
- Reliability, No false dumps for storage rings
- Activation, Handling, Safety
- Cooling power, Hydrolysis

LHC Dump with beam dilution



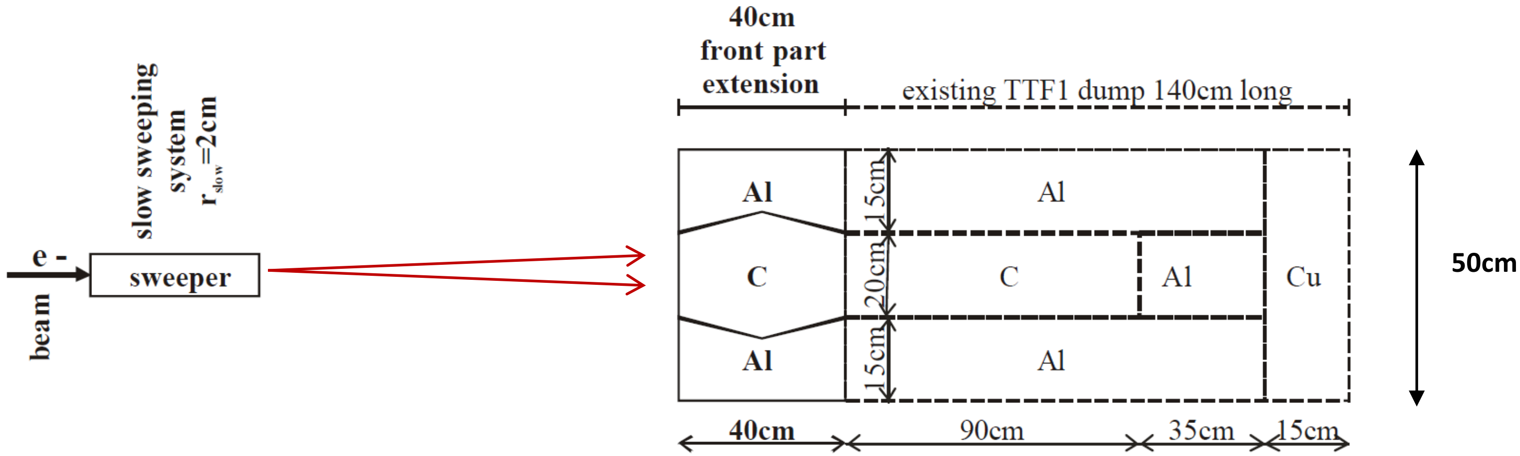


- the **ONLY** element in the LHC that can withstand the impact of the full 7 TeV beam !
- the dumped beam must be painted to keep the peak energy densities at a tolerable level !

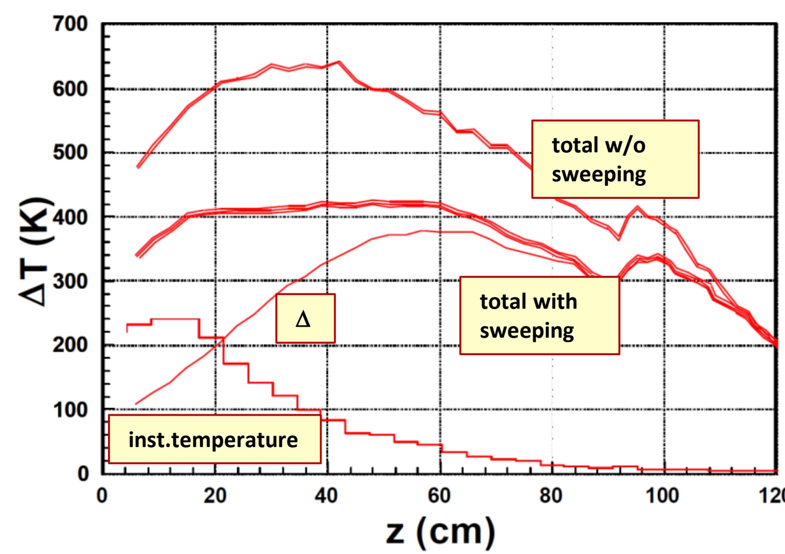


[courtesy: CERN/LHC team]

Electron-Beam Dump



- material composite with increasing density along *z*
- E_{inst} = 13kJ per bunchtrain (shock heating)
- P_{avg} = 130kW



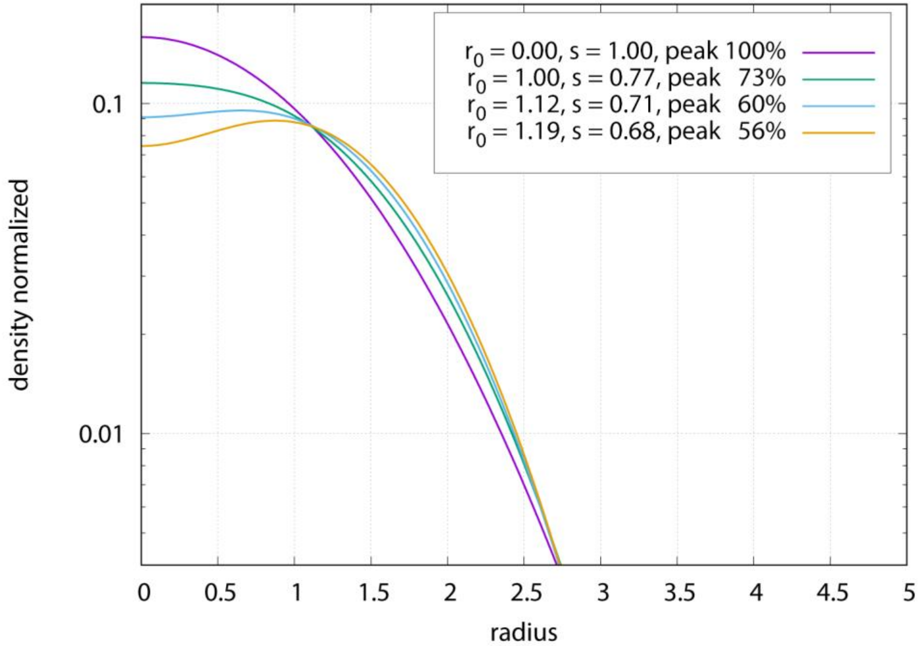
[Flash/DESY Hamburg, Maslov, Schmitz et al.]

Beam Rotation/Rastering of CW beam

- Distribution of deposited energy over larger volume
- Reduction of peak load vs average volume load

Example: **circular rotation of CW Gaussian beam**

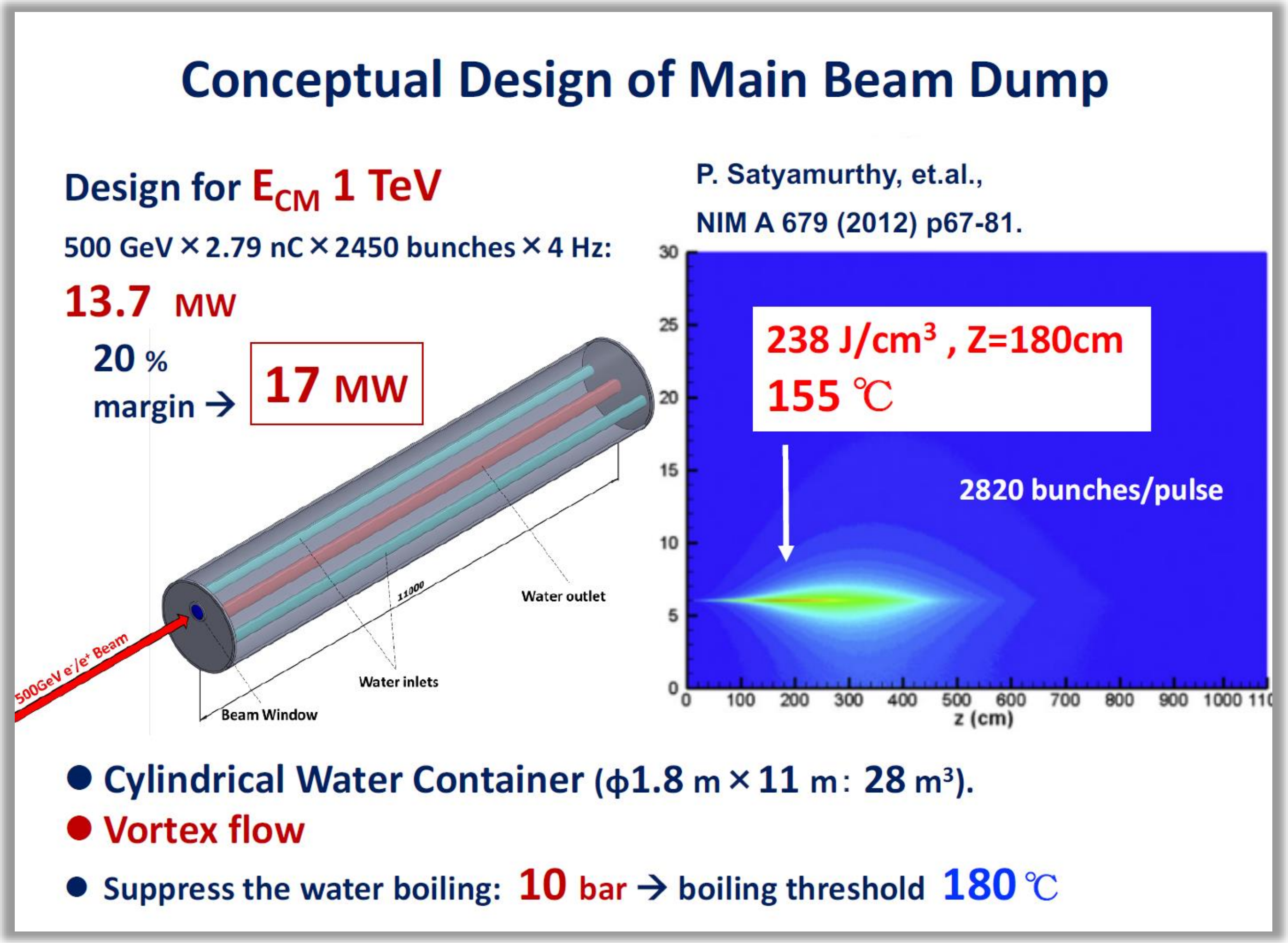
Varying beam size and rotation radius to keep outer radius fixed
Note: log scale



$$q(r) = \frac{q_0}{2\pi\sigma^2}\exp\left(-\frac{r^2+r_0^2}{2\sigma^2}\right)\mathrm{I}_0\left(\frac{r r_0}{\sigma^2}\right)$$

r_0 = rotation radius
σ = s = beam rms size
I_0 = Bessel Function

ILC Beam dumps



Specific issues:

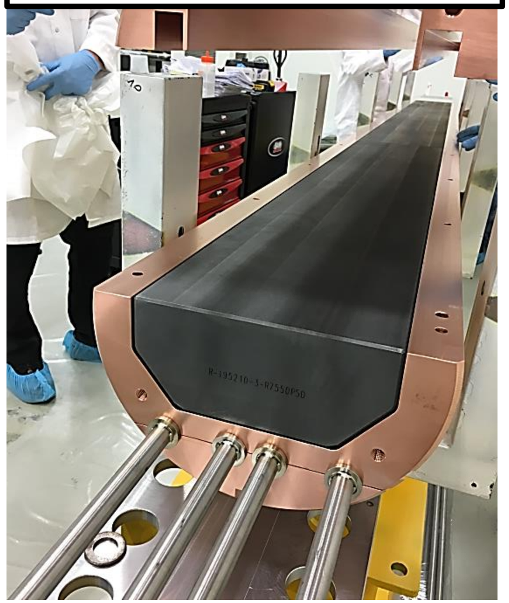
- Small beam size
- High avg. power
- Window(!)
- ^{3}H, ^{7}Be in water
- Hydrolysis (O_2 H_2)

[courtesy N.Terunuma, KEK]

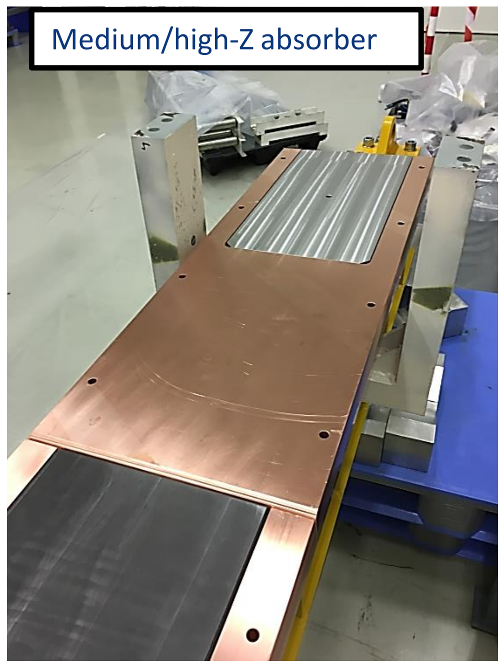
[ILC-DUMP]

state of the art CERN beam dump for SPS

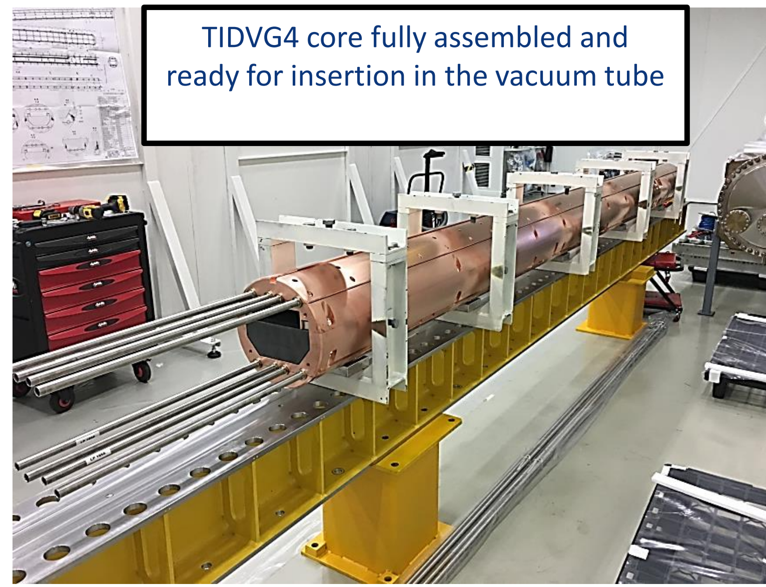
- Vacuum tightness is ensured by a seamless 316L tube – **no welds inside the shielding**
- 3.5 m **Graphite**, 40 cm **Cupro-Chrome-Zirconiu**m (CuCrZr) and 40 cm Inermet (**Tungsten**)



Graphite inside the CuCrZr core



Medium/high-Z absorber



TIDVG4 core fully assembled and ready for insertion in the vacuum tube

[courtesy: F.Bordry et al, FCC week 2017]

Summary

- Collimation systems remove large amplitude particles from the beam and localize these unwanted losses; Collimation systems protect sensitive components from mis-steered beams and excessive losses
- Optimizing a collimation system is a multi-physics problem, including
  - Beam dynamics, wakefields, cleaning efficiency
  - Numerical simulations from particle tracking to finite element calculations
  - Heating, mechanical stress and radiation damage
  - Operational aspects
- Beam dumps are designed to accept the full beam, allowing safe abort of circulating beam or continuous abort of CW beam
- Depending on parameters, electrons vs. hadrons, CW vs. pulsed, beam power and size, varying designs are required for collimators and dumps

Collimators and Dumps – some References

[LHC-COLLI] O.Büning (ed) et al, The LHC Design Report:

Beam Cleaning and Collimation, p467 (2004)

Beam Dumping System, p441 (2004)

[STRESS] P.Sievers, Elastic Stress Waves in Matter due to Rapid Heating by an Intense Particle Beam, CERN BT/74-02 (1974)

[HEAT] M.Seidel, An Exit Window for the TESLA Test Facility, DESY, 1995

[HERA-COLLI] M.Seidel, PhD Thesis, The proton collimation system of HERA , DESY 94-103 (1994)

[WAKE] D. Onoprienko et al, Measurement of Resistivity Dominated Collimator Wakefield Kicks at the SLC , EPAC Paris (2002)

[ILC-DUMP] P. Satyamurthy, et.al., Design of an 18 MW vortex flow water beam dump for 500 GeV electrons/positrons of an international linear collider, NIM A 679 (2012) p67-81.