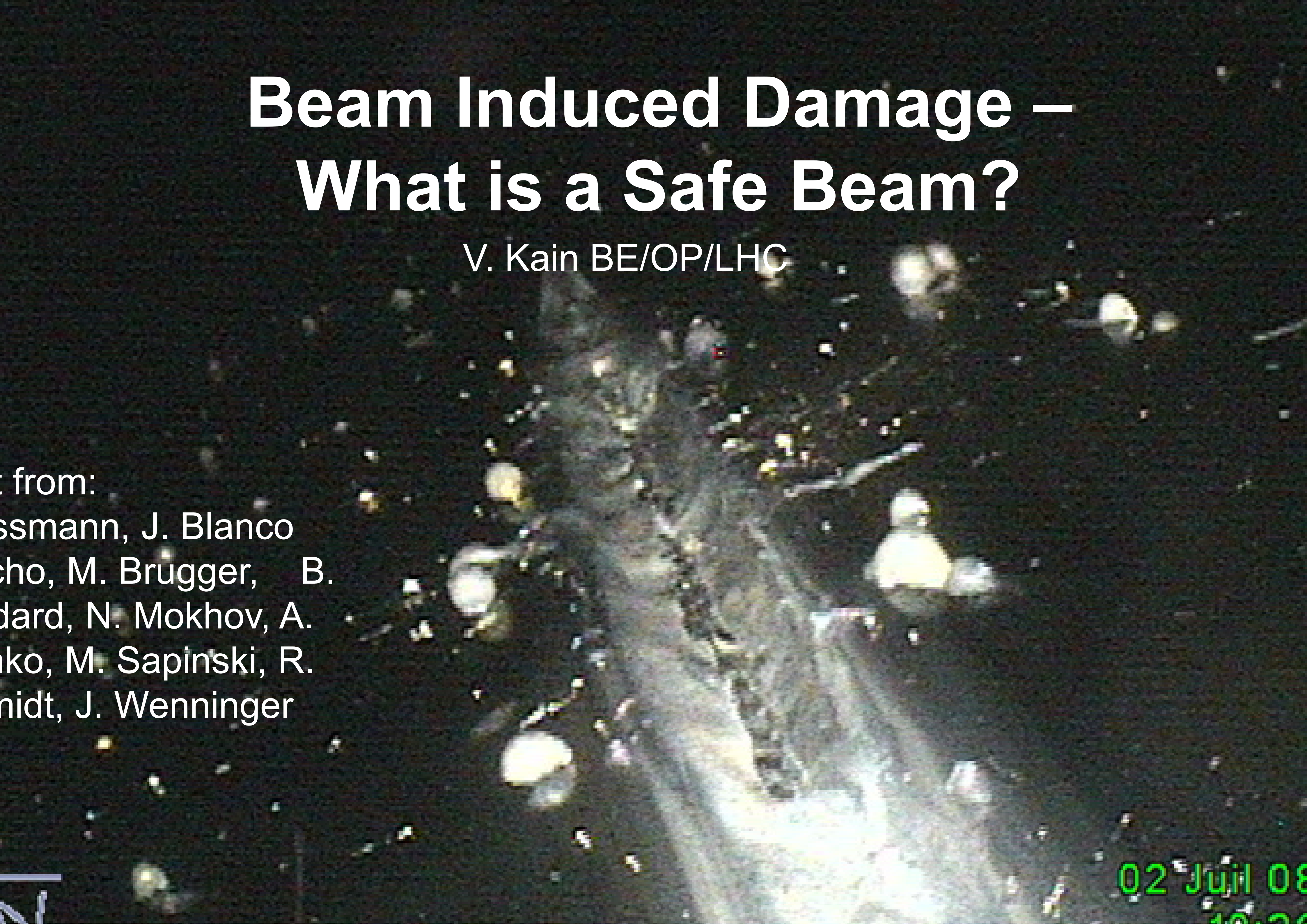
Beam Induced Damage – What is a Safe Beam?

V. Kain BE/OP/LHC

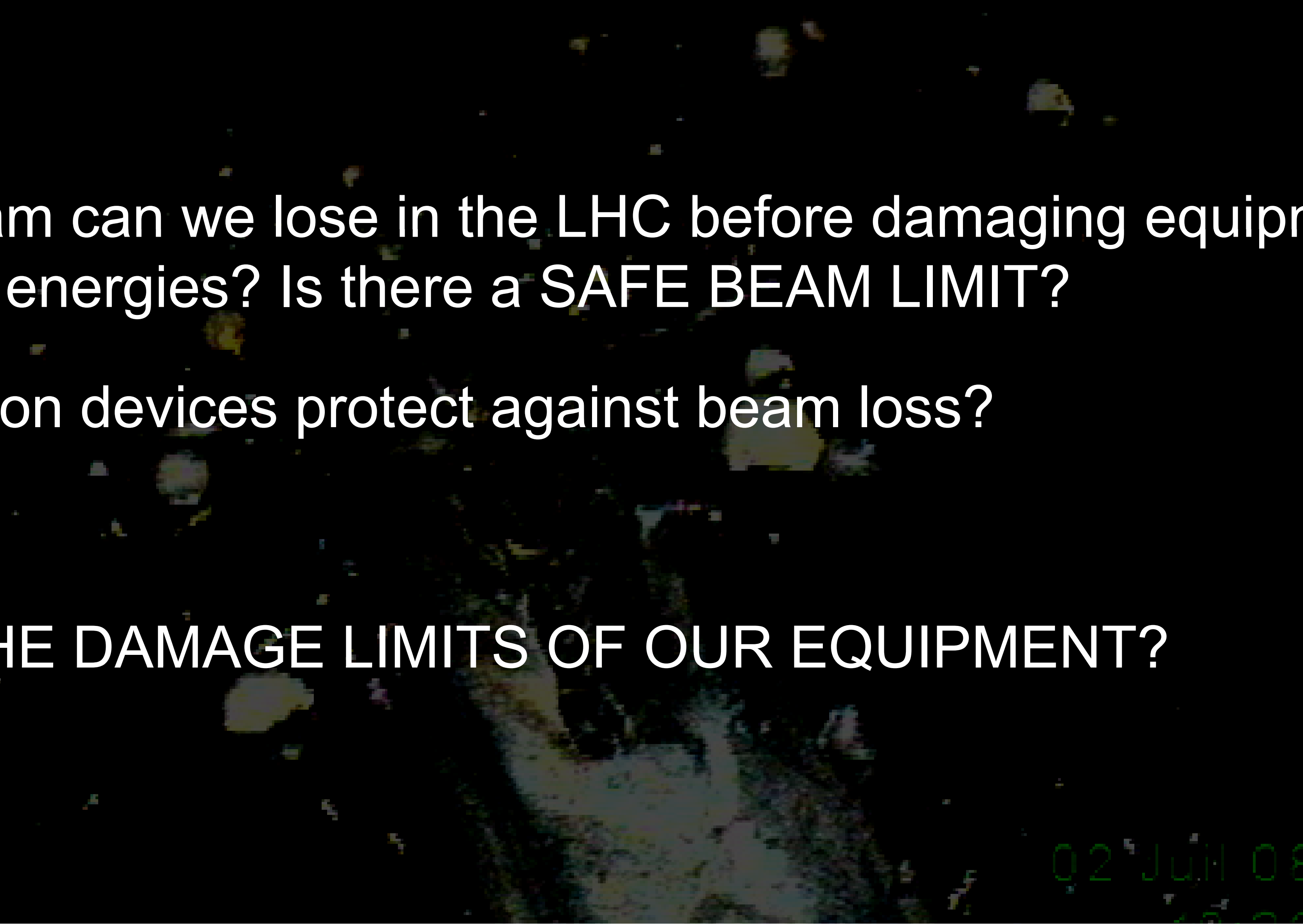


t from:
ssmann, J. Blanco
cho, M. Brugger, B.
dard, N. Mokhov, A.
nko, M. Sapinski, R.
midt, J. Wenninger

and had to be replaced.

l LHC injected batch is 3.2 x 10^{13} protons at 450 GeV. The full intensity is 3 x 10
protons which will be ramped to 7 TeV (360 MJ).

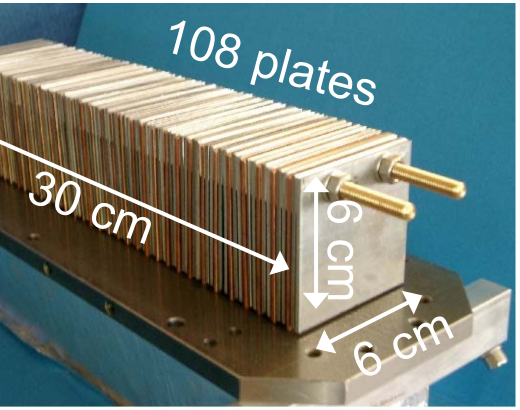
- How much beam can we lose in the LHC before damaging equipr
  at the different energies? Is there a SAFE BEAM LIMIT?
- Do our protection devices protect against beam loss?
- WHAT ARE THE DAMAGE LIMITS OF OUR EQUIPMENT?

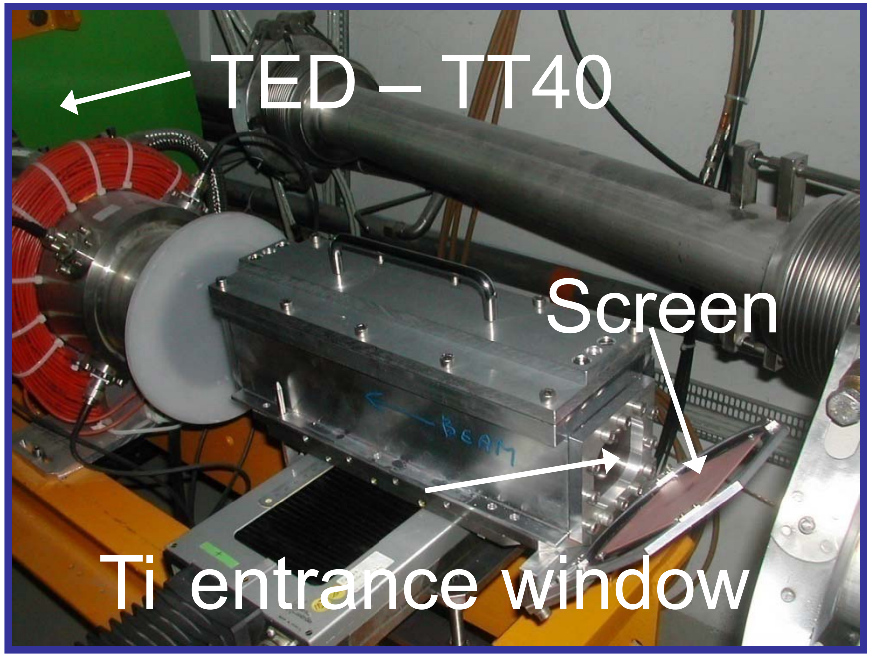


ots of metal in the LHC....

TT40 material damage test” was carried out

Experimental cross-check of damage limits of metals derived with FLUKA simulations





our intensities:

A=$1.3x10^{12}$, B=$2.6x10^{12}$, C=$5.3x10^{12}$, D=$7.9x10^{12}$

Perpendicular impact

amage = “clear sign of melting”

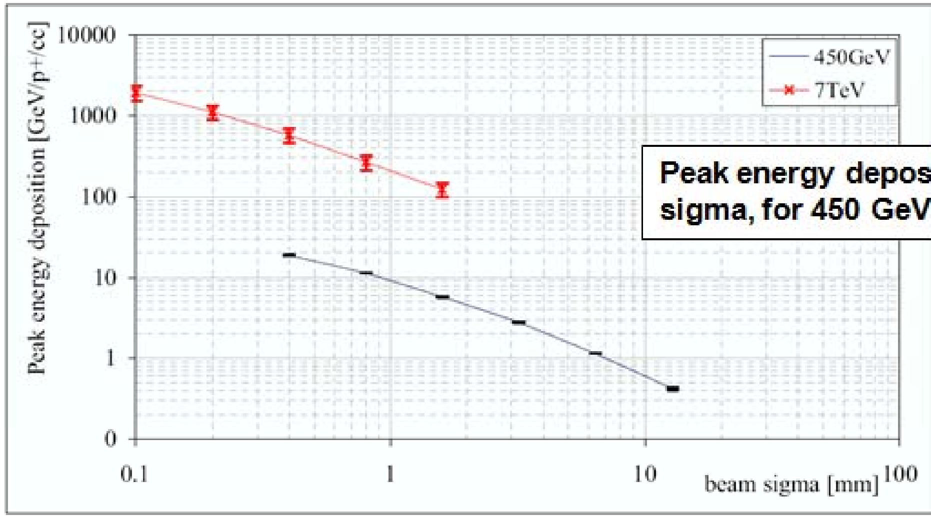
afe Beam Limit = Intensity where interlock inputs can be masked.

rom TT40 experiment: @ 450 GeV: safe limit = 1 x 10^{12} protons (intensity A)

laximum temperature for intensity A in TT40 experiment: ~ 500º C

Cu melting point: 1083º C

limit energy dependent:
caling law from FLUKA
imulations



Peak energy deposition E_{dep} in Cu vs beam sigma, for 450 GeV and 7 TeV protons

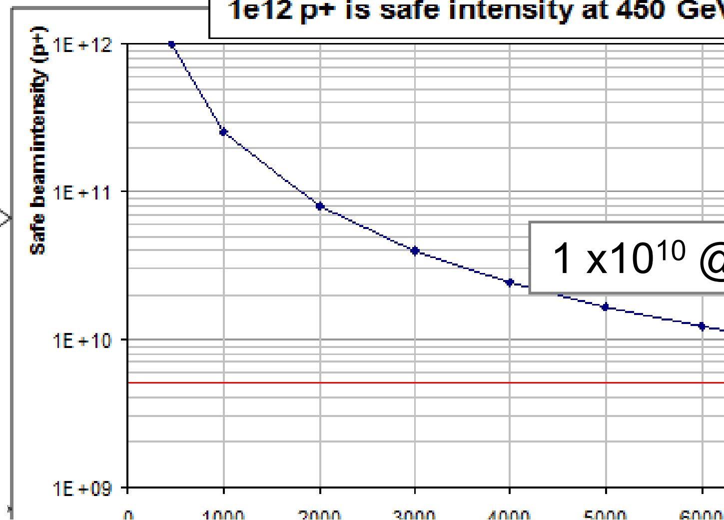
e Beam Limit
1 x 10^{12} $(450/E)^{1.7}$

estimate $E_{dep} \propto E^{1.7}$

(includes effect of emittance reduction)

For nominal emittance!!

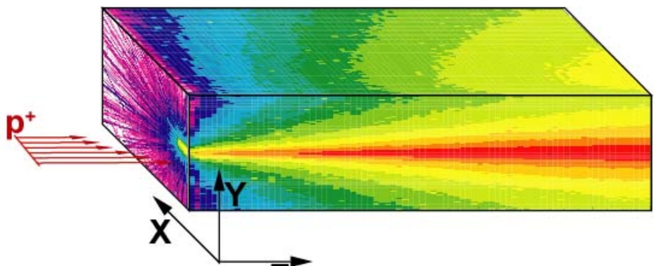
Safe beam intensity vs energy, ass
1e12 p+ is safe intensity at 450 GeV



xample: LHC secondary collimators

Allowable stress level: σ_s = 86 MPa

Studied worst case impact scenarios: injection error, 7 TeV asynchronous dump, 7 TeV pre-fi



FLUKA result

ANSYS →

450 GeV

Material	Jaw length [cm]	Max. temperature [°C]	Stress σ_{equiv} [MPa]
Carbon-Carbon	20	335	4.4
	100	345	12.7

7 TeV

Material	Jaw length [cm]	Max. temperature [°C]	Stress σ_{equiv} [MPa]
Carbon-Carbon	20	212	20.8
	100	551	82.0

R. Ass

Melting point of C ~ 3500° C. Mechanical limit already reached at 551° C. Factor 7 below me

xample: TPSG in the SPS: absorber in front of the extraction septa for fast extra

TPSG in LSS6: 3.5 m long sandwich of different materials (graphite, titanium, INCONEL)

Safety limit for material integrity: 305° C in one of the graphite blocks.

xample: LHC Secondary Collimator: TT40 robustness t

Considered accident case at injection:

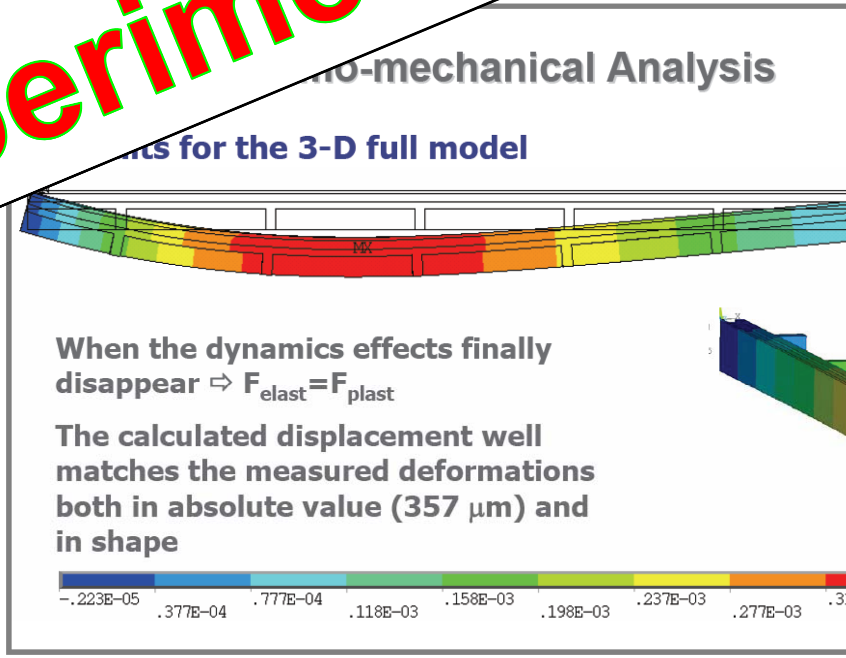
- o 2.4 MJ/mm2: 3.2 x 1013 protons @ 45

Graphite jaw survived as

But: therma upport bar deformed the whol C

Now: Cop® support bar instead of Cu

Discovered by experiment



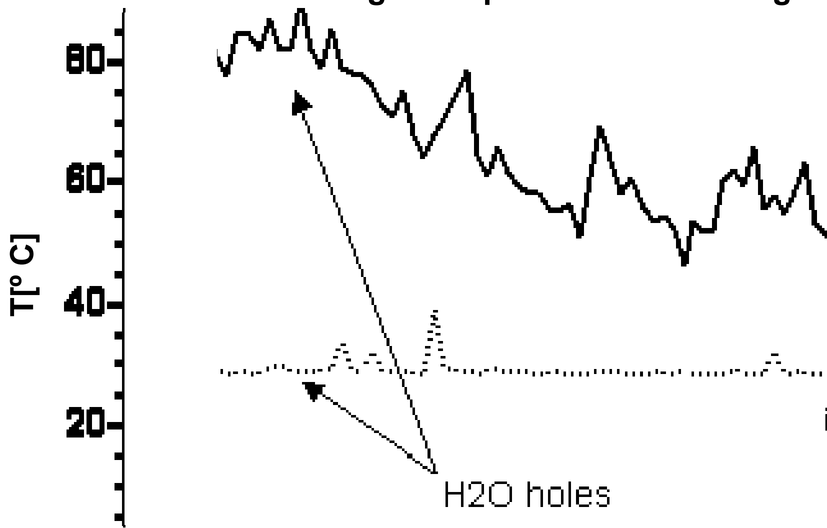
A. E

xample: TPSG in the SPS

TPSGs needed re-designing to survive stresses during impact

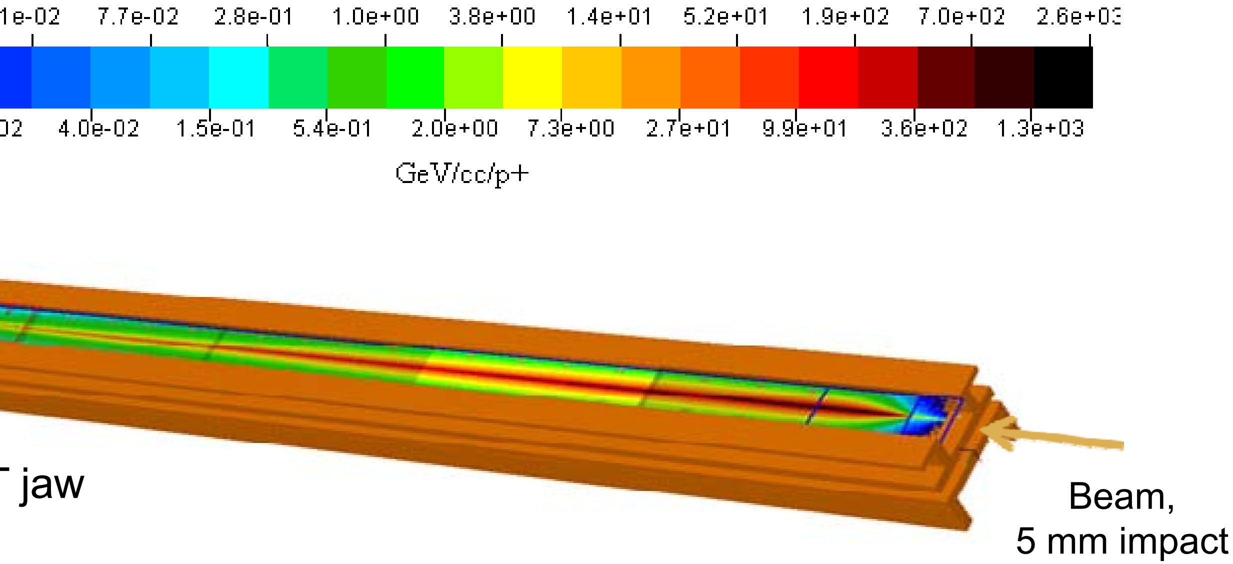
However: design had to be adjusted again

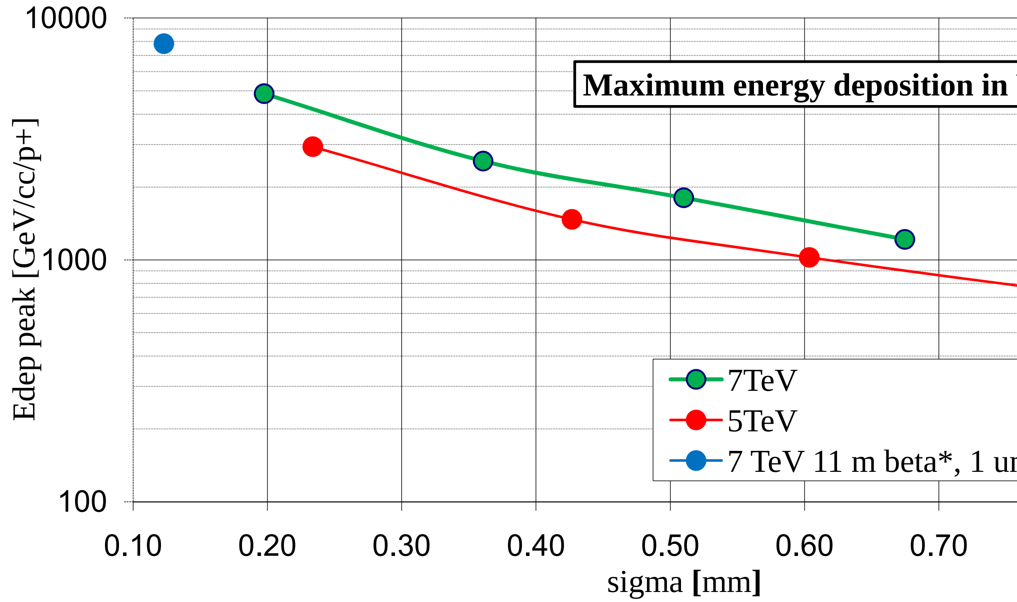
- o Temperature rise 50 K → 250 bar pressure rise in water cooling system of septa too high during impact.

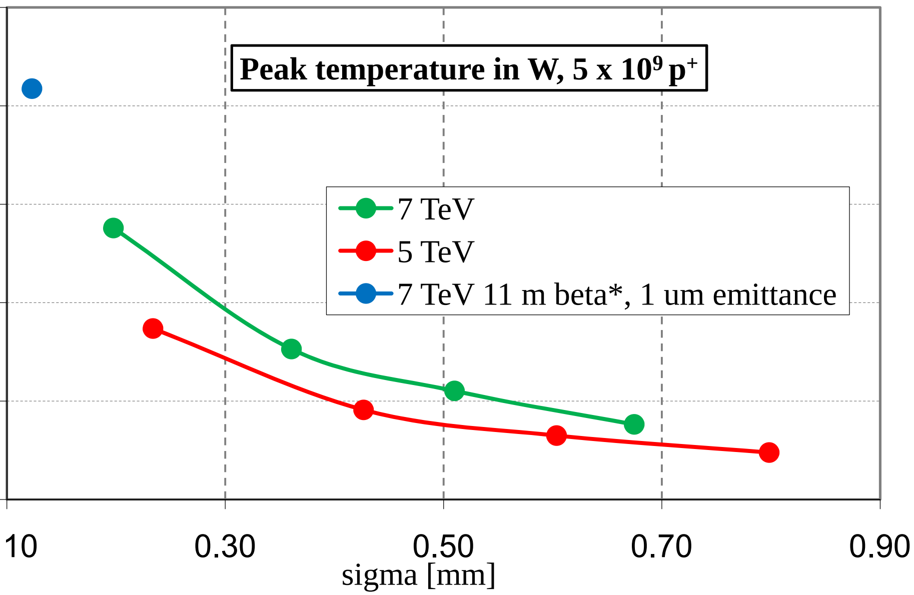


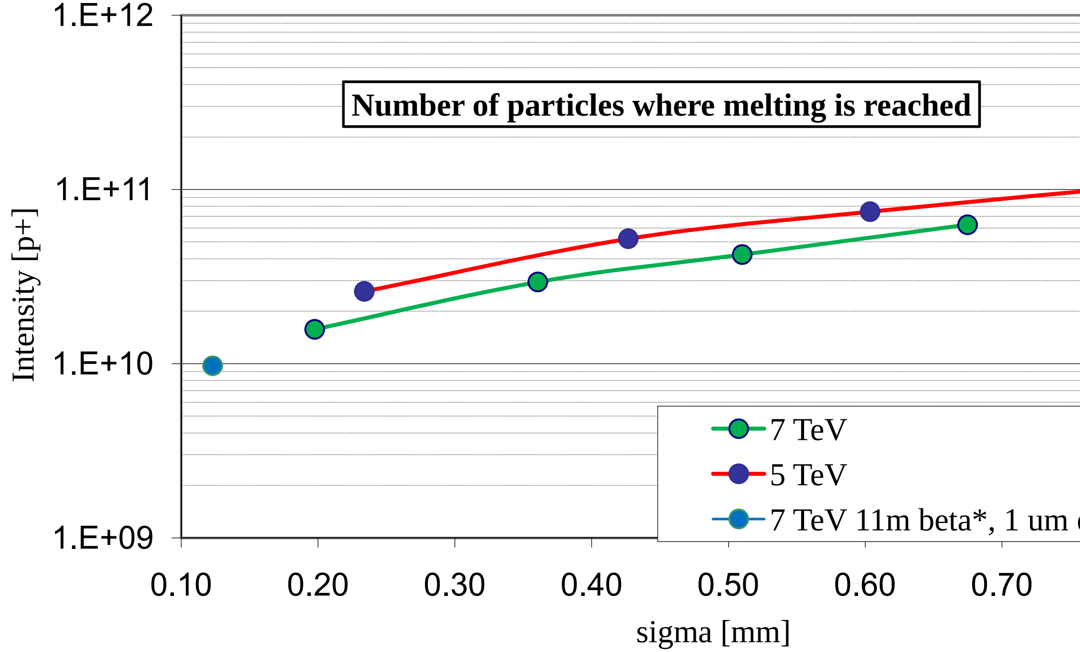
he tertiary collimators close to experiments are made of W to protect triplets wit
queezed beams at 7 TeV.

J. Blanco Sa









sten melting point: 3422° C

YES....

afe Beam Intensity is required as "set-up" intensity, **not** as intensity which can b
afely lost **under all conditions**!

Set-up" intensity for collimator setting-up, optics measurements,...with relaxed
achine protection constraints (masking)

Constraint #1: needs to be safe for slow losses (BLMs will protect)

Constraint #2: needs to be measureable with instrumentation

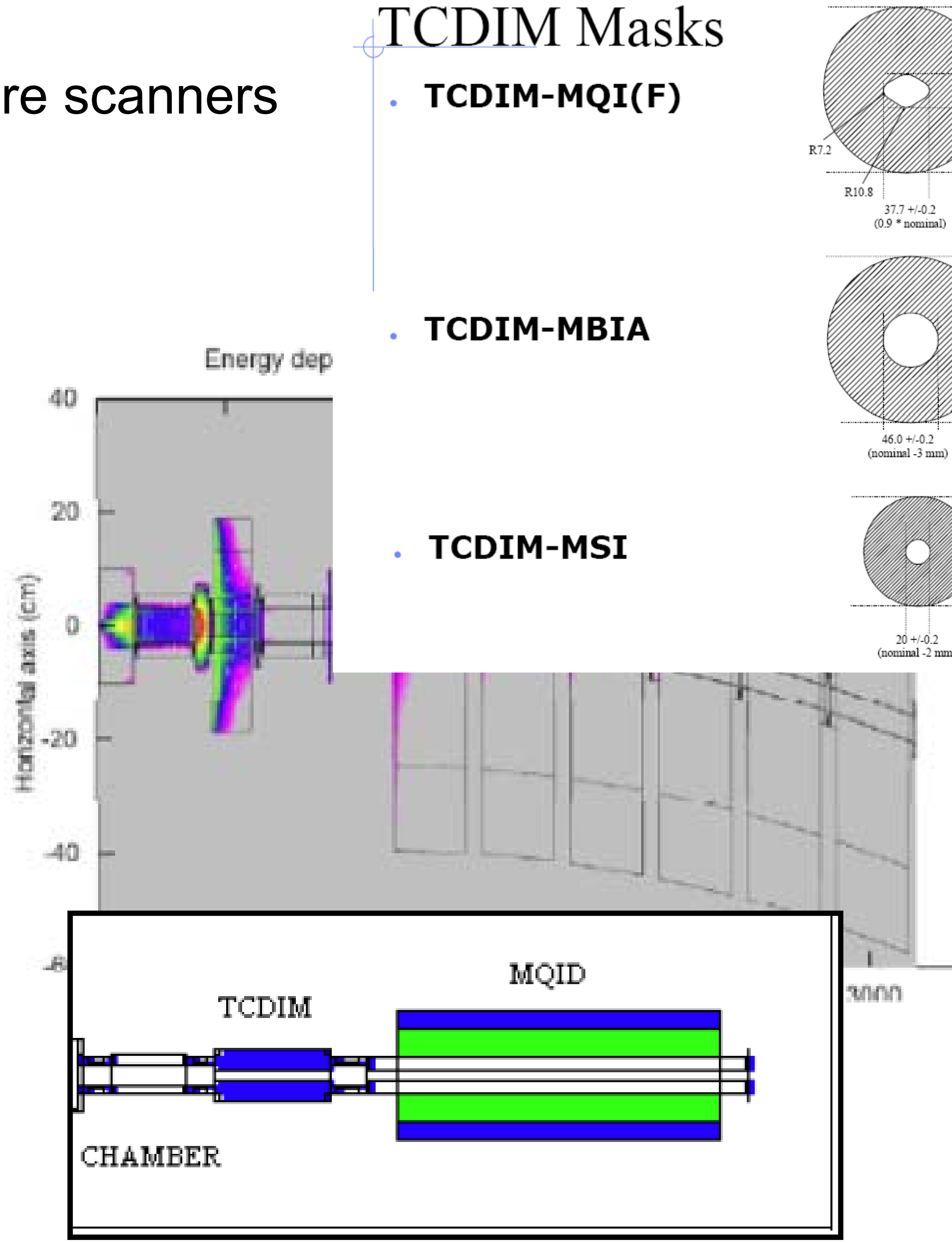
- pilot intensity at 7 TeV

roposal: **change name** from

afe Beam Intensity/Flag → **Set-up Beam Intensity/Flag**

leed to know the “REAL” damage levels of equipment to:

- set operational limits for equipment: e.g. Screens, wire scanners
  - o Already fairly well-known and agreed
- set BLM thresholds to protect the element: e.g. TCT
- **design passive protection: masks and absorbers**



xample: Transfer line collimation system

- Damage level of magnets: coil > 100º C
- Beam loss on the collimators heats up downstream magnets: FLUKA simulations
- → masks had to be introduced

Protection devices in the LHC: similar situation as in the LHC

Injection protection: TDI – TCDD (mask) – D1 (superconducting)

Dump protection: TCDQ – TCDQM (mask) – Q4 (superconducting)

HOW WELL DO WE KNOW THE DAMAGE LEVELS OF SC MAGNETS?

Is there one for all?

4.5 K and 1.9 K magnets, MBs and triplets?

LHC Project Note 141 (O. Bruning and J.B. Jeanneret), 1998

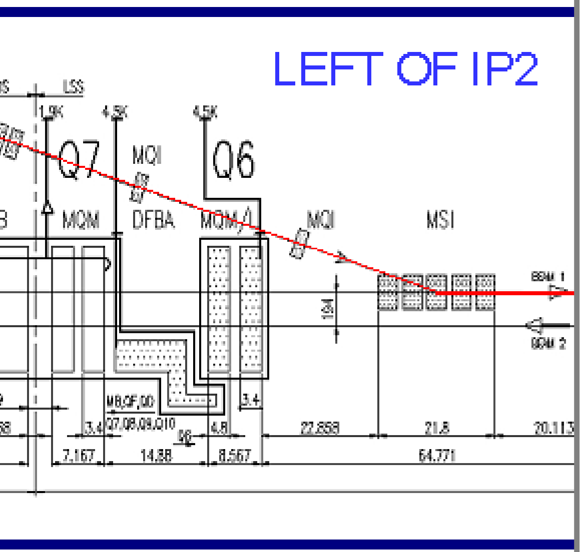
Damage level of superconducting magnet

The equation (21) solves with $T_c = 104$ K. The critical energy deposition per unit volume is obtained by integrating numerically (22) between $T = 0$ and $T = T_c$, or

$$\Delta Q_c = 87 \text{ Jcm}^{-3}. \quad (23)$$

Further down they state [required number of protons to be lost at one location to damage]:

his damage level for SC magnets has been used for designing the TDI-TCDD rotection...

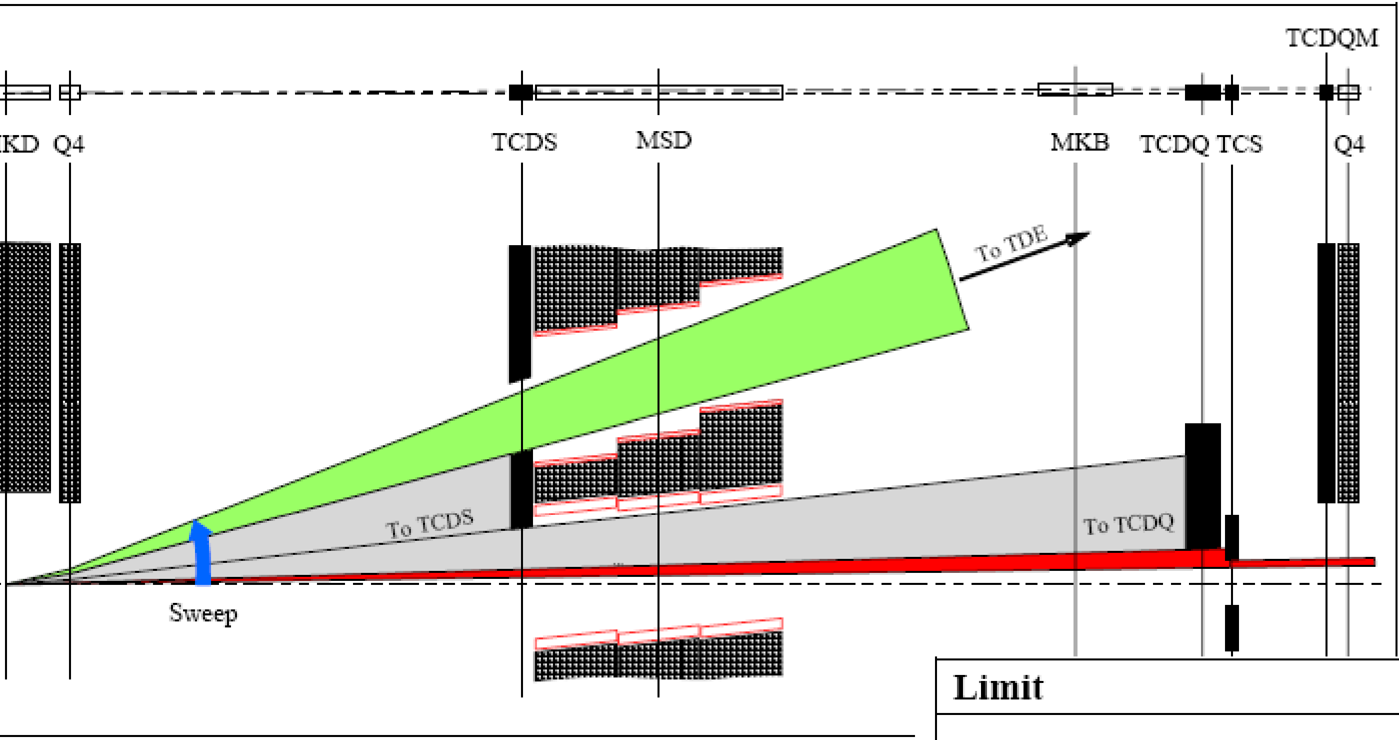


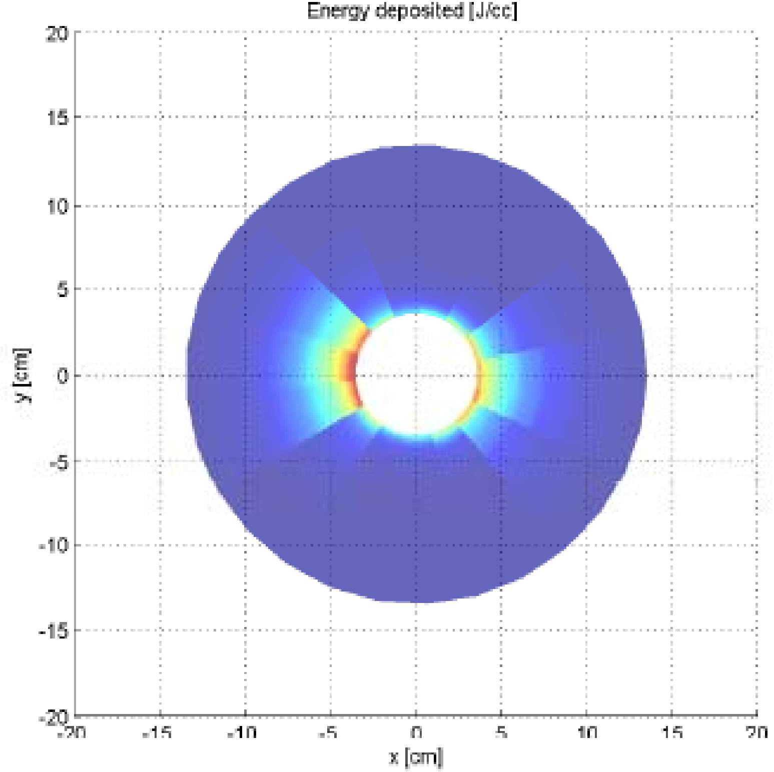
CASE GRAZING: comparison

TCDD	TDI	Energy deposition on D1			
		GeV/cm³/p	*J/cm³*		
			1.1 10^{11}p	**3.17 10^{13}p**	**4.9 10^{13}p**
Absent	New	7.35 10^{-3}	0.13	37.33	57.70
	Old	1.4 10^{-2}	0.25	71.10	110.0
1500 mm²	New	5.90 10^{-4}	1.04 10^{-2}	3.0	4.63
	Old	8.1 10^{-4}	1.43 10^{-2}	4.11	6.36
3600 mm²	New	2.76 10^{-3}	4.86 10^{-2}	14.02	21.67

- New TDI geometry seems to be better than the old one, according to the simplified configuration results (a factor 2 due to the BN used has to be considered!!).
- Safety factor 1.5 (*damage* level = 87 J/cm³): TCDD is still needed to prevent *damage* in all conditions.
- With an identical TCDD configuration (but different position) the improvement due to TDI is still evident, in spite of the worsening due to the position of TCDD.
- Enlarging the TCDD opening to the actual size, it can be seen that the overall effect is negative.

.and these levels also were used for the dump pro





Limit	450 GeV	7 TeV
Damage; instantaneous deposition [5]	87 J/cm^3	87 J/
Quench; instantaneous deposition [6]	35 mJ/cm^3	4 mJ/
Quench; localised DC deposition [7]	1 - 10 mW/cm^3	0.2 - 5 mW/
Quench; total magnet power deposition [8]	34 W	3

Table 7. Summary of instantaneous load due to asynchronous dump at 7 TeV.

	peak load (J/cm^3)	ΔT (K)	Energy flow (J)
TCDQ (front)	2139	712	-
TCS (right)	2283	679	-
TCDQM	44.5	12.8	-
MCBY	26.2	-	262

During an asynchrono
dump the Q4 is protec
damage by the TCDQ

magnets?

According to the experts...

We don't know...

The only number available: 87 J/cc

pilot @ 450 GeV: 360 J

Is that number conservative?

A. Siemko: temperatures for components of SC magnets to start degradation

1. ~ 180º C: Kapton
2. ~ 220º C: SnAg solder material
   - important for splices
   - and cross-contact resistance of strands, strands are coated with SnAg
3. ~ 350º C: NbTi
   - current carrying capacity starts degrading
   - probably a more long term effect (days)

And shockwaves?

Contacted people from the TEVATRON

‘We don't have and never had a damage limit for the Tevatron superconducting magnets specifically. We have the solid numbers for slow and fast quench limits [...]’N.Mokhov

Vould be useful to clarify whether or not **87 J/cc** is conservative.

If not our protection might not be adequate.

Simulations should be carried out to address energy deposition from transient be
oss!

Experimental verification?

We might get some data from the LHC...clearly not preferred solution

TT60 HiRadMat (High Power Beam Test Facility)?

Proposal for HiRadMat in TT60:

- Address **immediate need** for LHC collimator upgrade.
- **Foster advances in basic understanding of beam-induced shock waves** in standard and advanced materials.

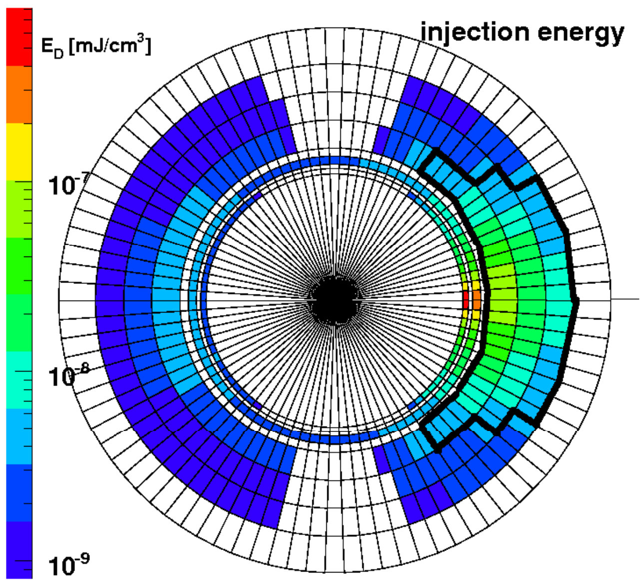
R.W. Assmann

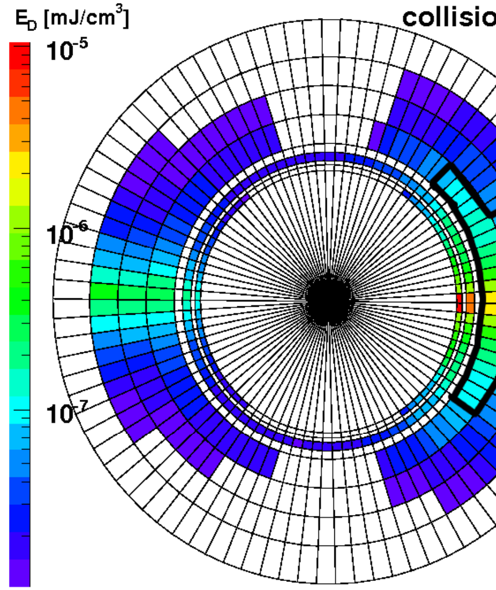
- Could we irradiate a **COLD** SC magnet there?

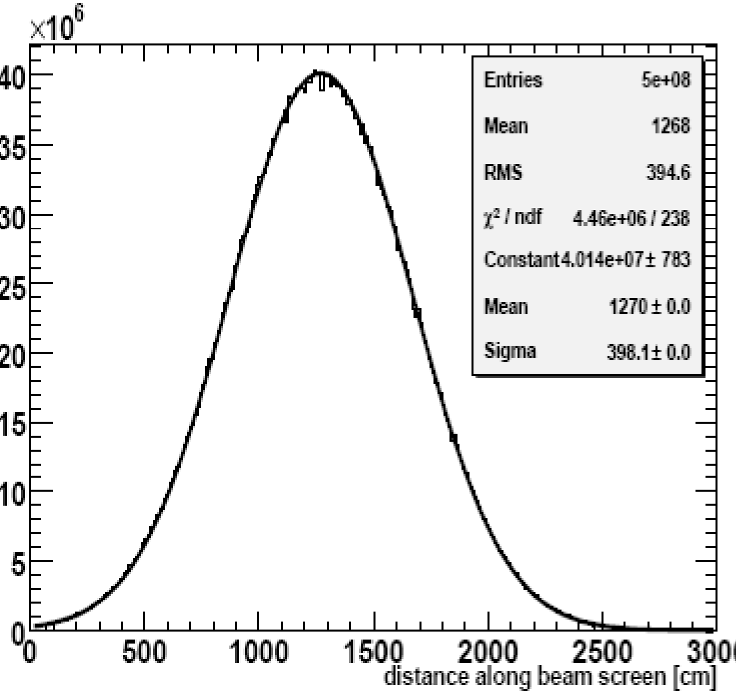
Simulations with Geant4 by
M. Sapinski

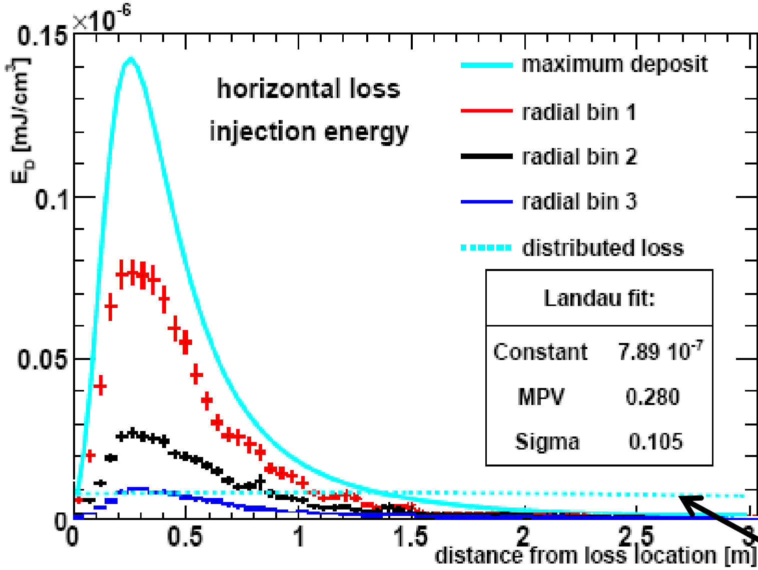
Distributed losses due to small impact angles:

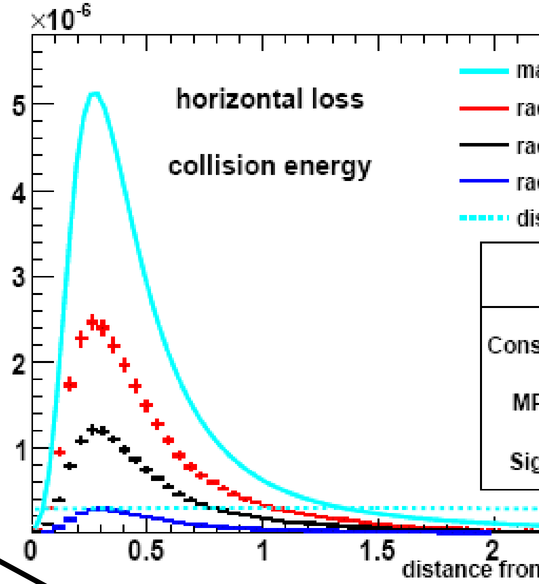
Quench of MB in sector 23: impact angle: ~ 250 μrad, beam size: 1 mm











Energy deposition in the coils of a main dipole after be

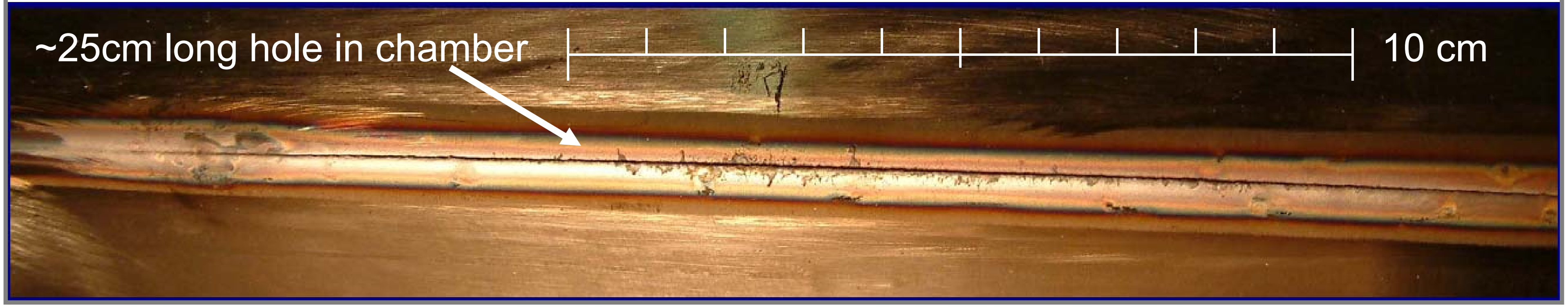
Energy deposition maxima in the cold bore/beam screen.

Point like losses on vacuum chamber:
Injection: 1 x 10^{12} p^+: 150 J/cc > 87 J/cc

Distributed los

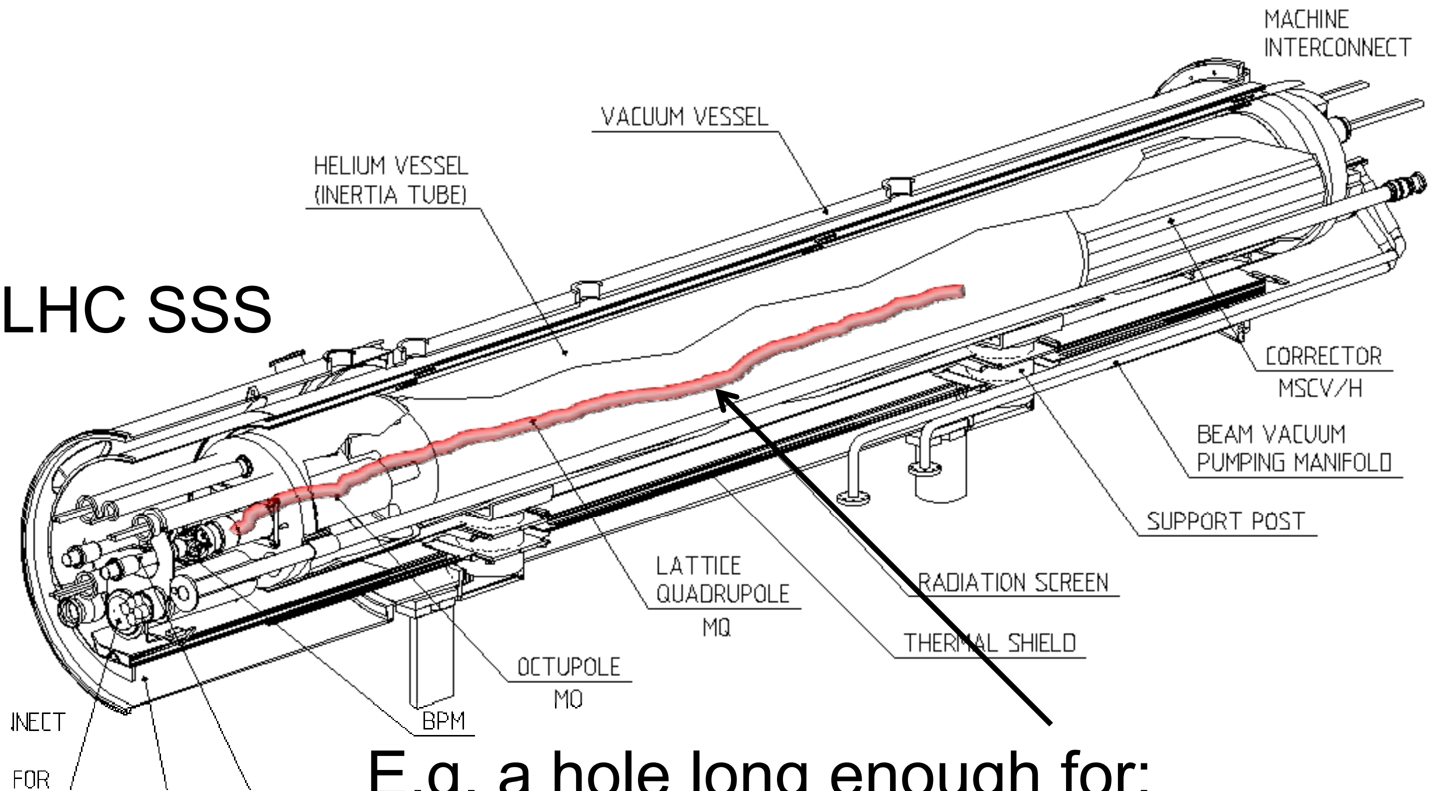
rom the TT40 incident we know: holes are “long” **slits**

25th of October 2004: MSE trip during high intensity LHC extraction. Damage of QTRF pipe and magnet.



s it possible to slice open an LHC SC magnet and recreate a S34 incident?

An LHC SSS



E.g. a hole long enough for:

or the case studied on the previous slide he energy deposition for the cold bore by M. Sapinski

Distributed losses: (assuming 316L, onstant Cp):

Melting point for 316L: 1398° C

mperature Rise Estimate over several m:

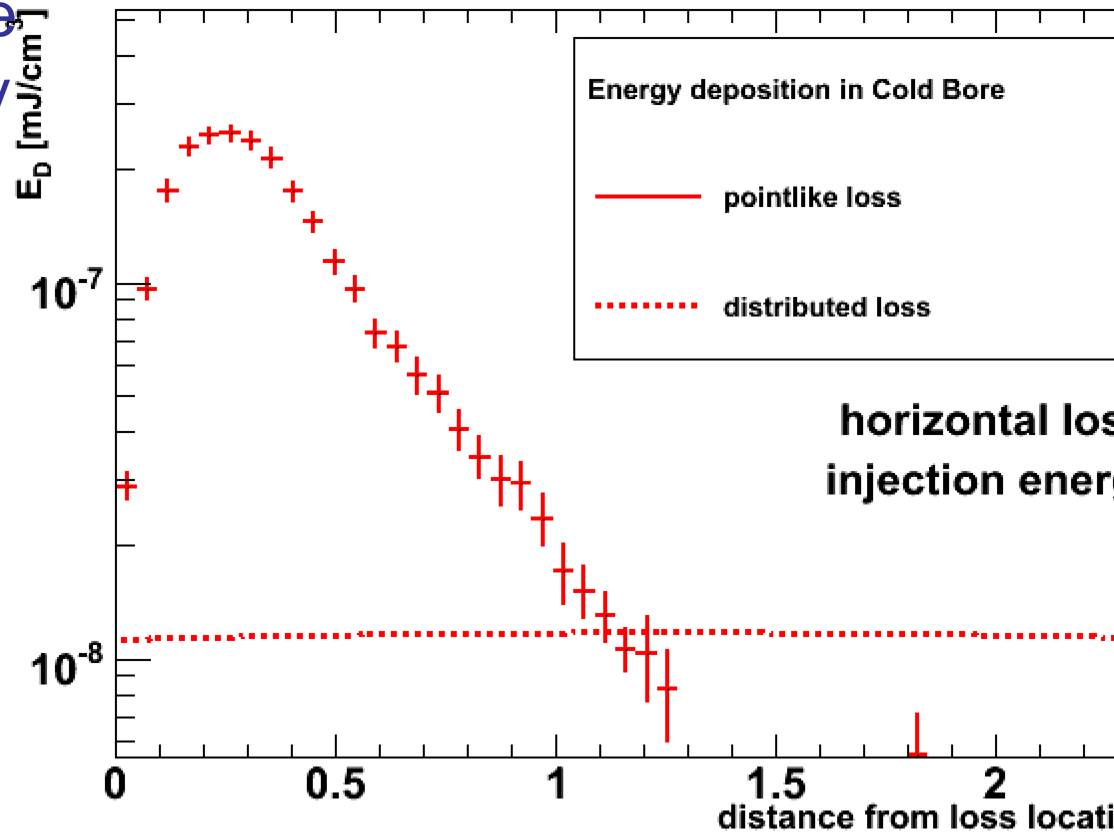
Injection: 1×10^{12} p^+ : $\Delta T \sim$ 76 K

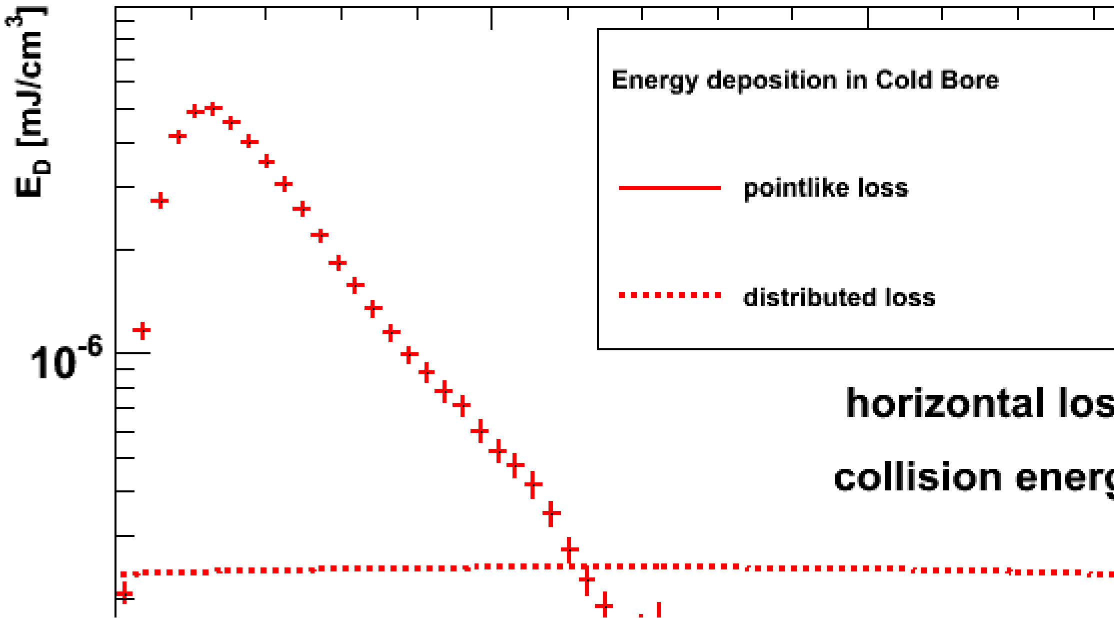
o 3.2×10^{13} p^+ : $\Delta T \sim$ 2100 K

Collision: 1×10^{10} p^+ : $\Delta T \sim$ 13 K

o 1×10^{12} p^+ : $\Delta T \sim$ 1050 K

Preliminary numbers. Outcome very ensitive to impact angle, input istribution!!, aperture details,...





Our "set-up" intensity limits derived from the damage experiment seem to be con
with damage limits derived through other means (Note 141).

Not every equipment (RF cavities, injection kickers,...) has been studied.

Damage level of superconducting magnets?

Shock waves, dynamic effects, phase transitions,...: damage levels are difficult to
estimate → **experimental verification is useful → HiRadMat**.

For some equipment (e.g. Tertiary Collimators at 7 TeV) our "set-up" intensity is N
safe.

Plus: damaging potential depends very much on impact, emittance,...

ons?

By-product of our investigation: beam loss in SC magnets

Very first result: during accidents with large beam oscillations and large enough intensities sto
holes of several m length could be drilled into the cold bore...S34 incident?

More data soon from FLUKA studies using the IR7 dispersion suppressor model with realistic hould take conservative approach: **AT 7 TEV NO BEAM IS SAFE UNDER ALL CONDITIONS**

But should not panic either: need to get to 3×10^{14}

<u>mplications for operational strategy:</u>

AVOIDANCE

- o Make sure we stay within operational envelope (I, E, emittance)
- o Make every effort to prevent operational errors: RBAC, critical settings, SIS,...
- o Thoroughly prepare and follow the commissioning procedures

MINIMISE CONSEQUENCES

- o Set up and use passive protection from very early on
- o Even if cleaning is no issue yet, use collimators as passive protection
- o Every new intensity/energy step: use pilot intensity first
- o Minimise downtime: spares, He release valves,...

CONTINUOUS FOLLOW UP