ACCELERATOR
RELIABILITY
AVAILABILITY

L. HARDY, ESRF

THE BASICS

AVAILABILITY: fraction of **TIME** during which a system meets its specification.

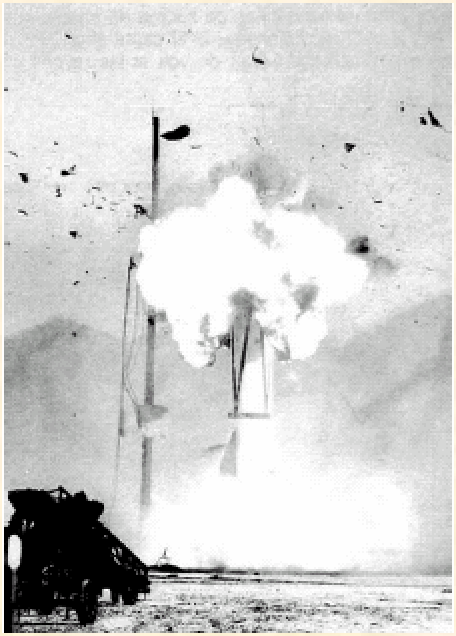
→ High availability required if continuous service is priority

RELIABILITY: **PROBABILITY** that a system can perform its intended function for a specified time interval under stated conditions.

→ High reliability required when repair of sensitive sub-components are long (or difficult)

A BRIEF HISTORY OF RELIABILITY…

1940 - 1944

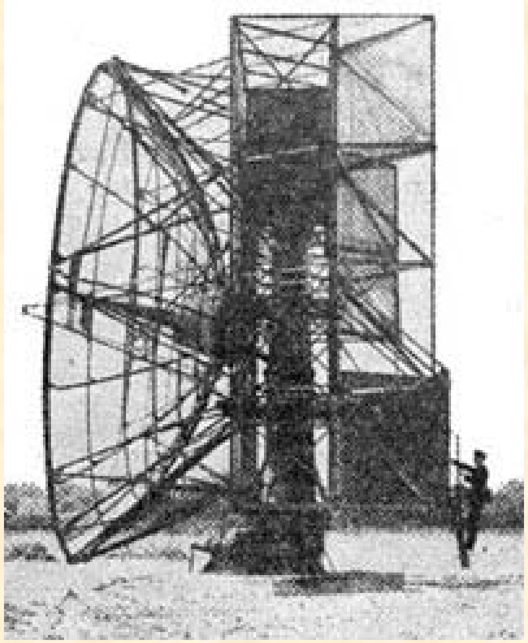


Rockets reliability

Mechanical reliability
(aging, stress)

$\neq$

electronic reliability
(random failures) →
First RELIABILITY MODELS including redundancy



Radar reliability

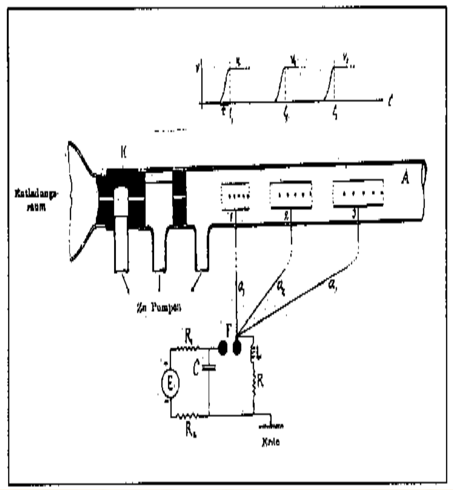
A BRIEF HISTORY OF ACCELERATOR NON-RELIABILITY…

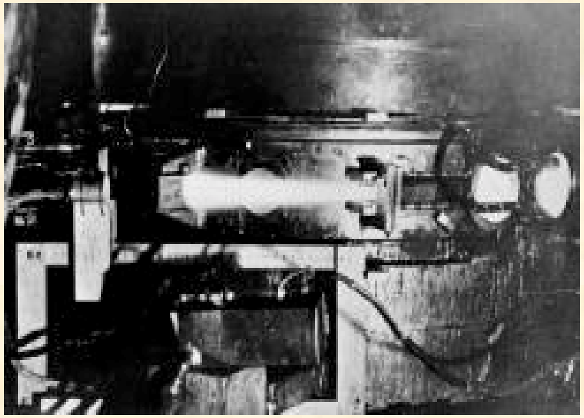
The race to accelerators physics principles…

1924: Ising: the first Linac model

1928: Wideröe: a model based on RF voltage

March 1936: the first external cyclotron beam: 5.8 MeV deuterons





A BRIEF HISTORY OF ACCELERATOR NON-RELIABILITY…

The race to higher intensities, higher energies…

1941: 184-inch cyclotron (>100 MeV) for U235 / U238 separation (Berkeley)

1947: proton Linac built under supervision of Alvarez

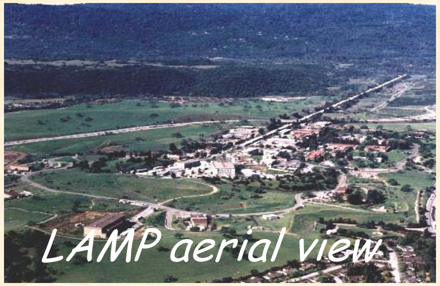
1959: CERN 24 GeV PS is the *highest energy* accelerator in the world

PS inauguration (1960)

A BRIEF HISTORY OF ACCELERATOR RELIABILITY…

(+ PSI, TRIUMF)

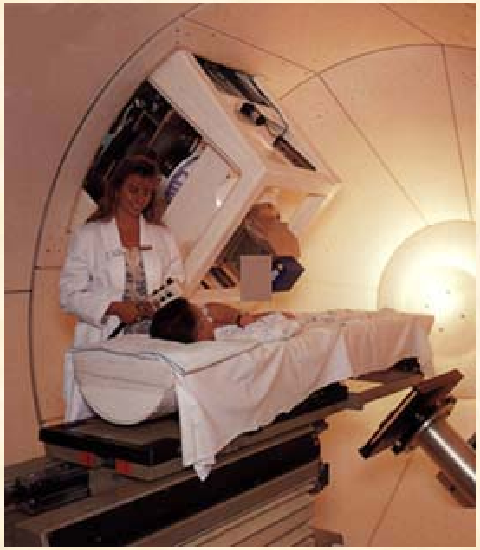
1972: ***meson factories***. *E.g.*: Los Alamos (LAMPF): 800-MeV beam achieved



Rosen: « more particles per unit time rather than more energy per particle ! »

1981: ***DEDICATED X-ray sources. First one is SRS (UK)***

MEDICAL APPLICATIONS



USERS WANT RELIABILITY AND AVAILABILITY !!

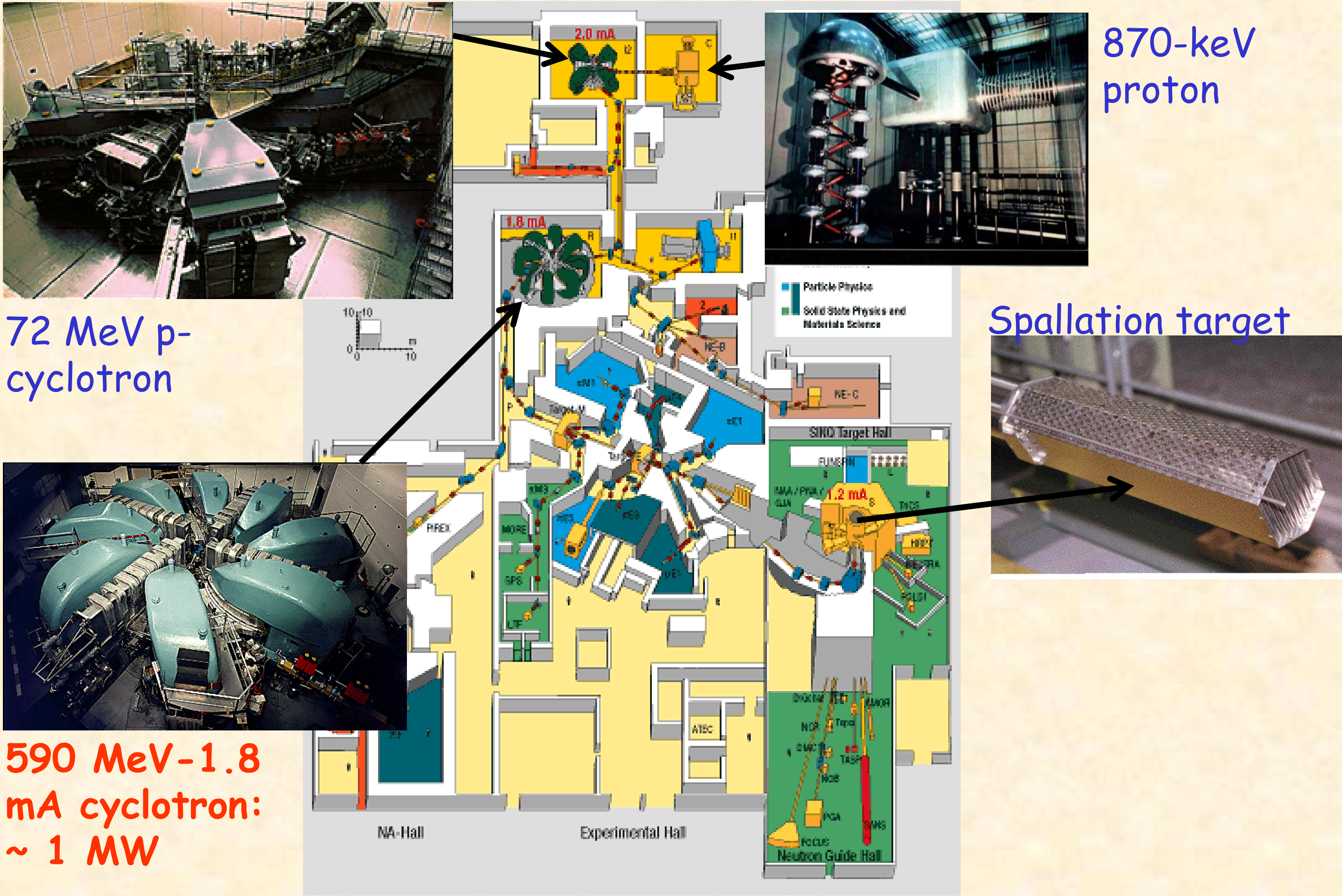
APPROACH WITH CONCRETE EXAMPLES

- **SINQ**: a continuous spallation source (Cyclotron-based)
- **LANSCE**: a pulsed proton source (Linac-based)

as examples of « extrapolable » accelerators for ADS

- **ESRF**: an X-ray source (Synchrotron-Storage Ring)

SINQ: a Continuous Spallation Source (Switzerland)



870-keV proton

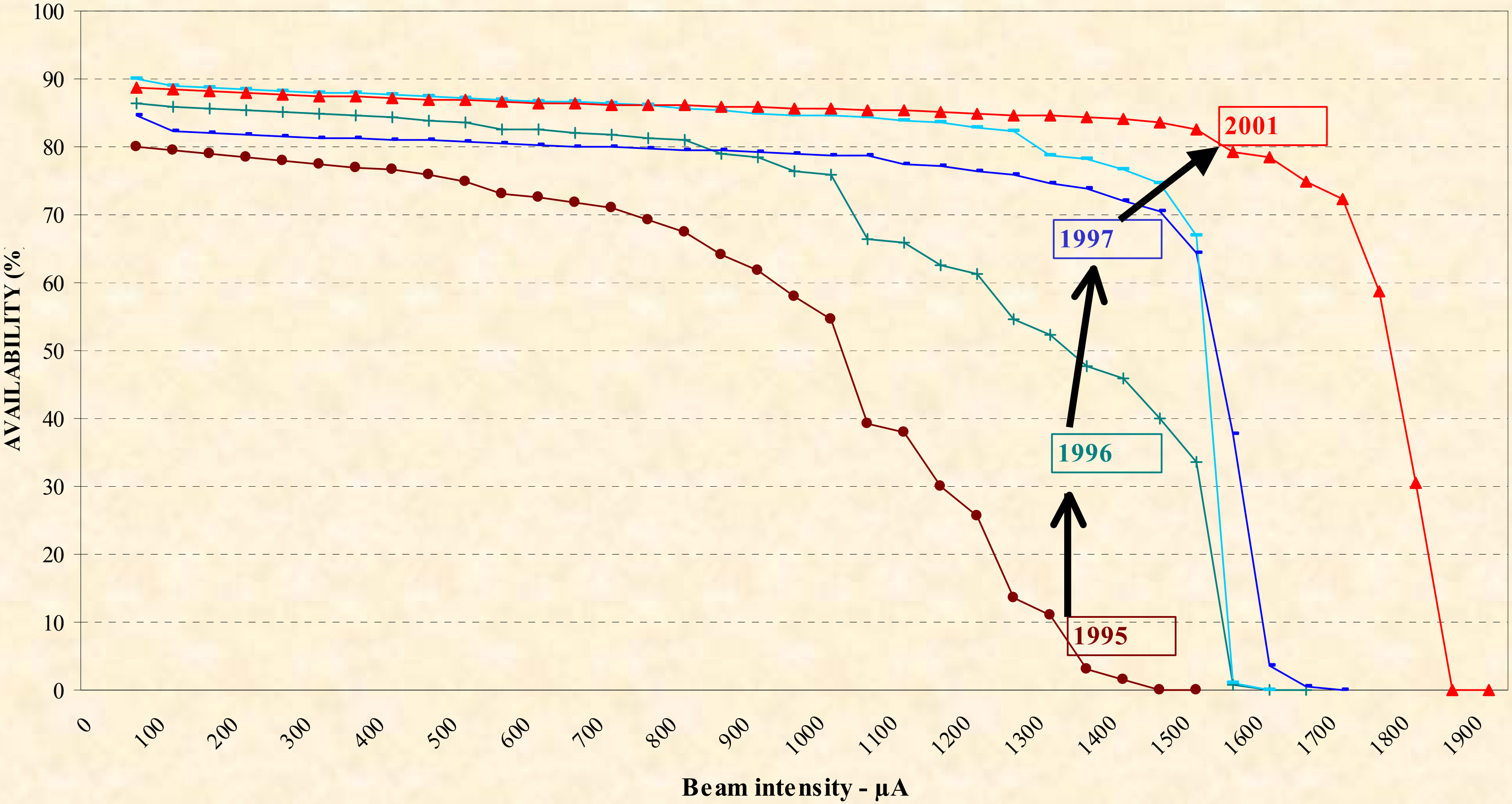
72 MeV p-cyclotron

Spallation target

590 MeV-1.8 mA cyclotron: ~ 1 MW

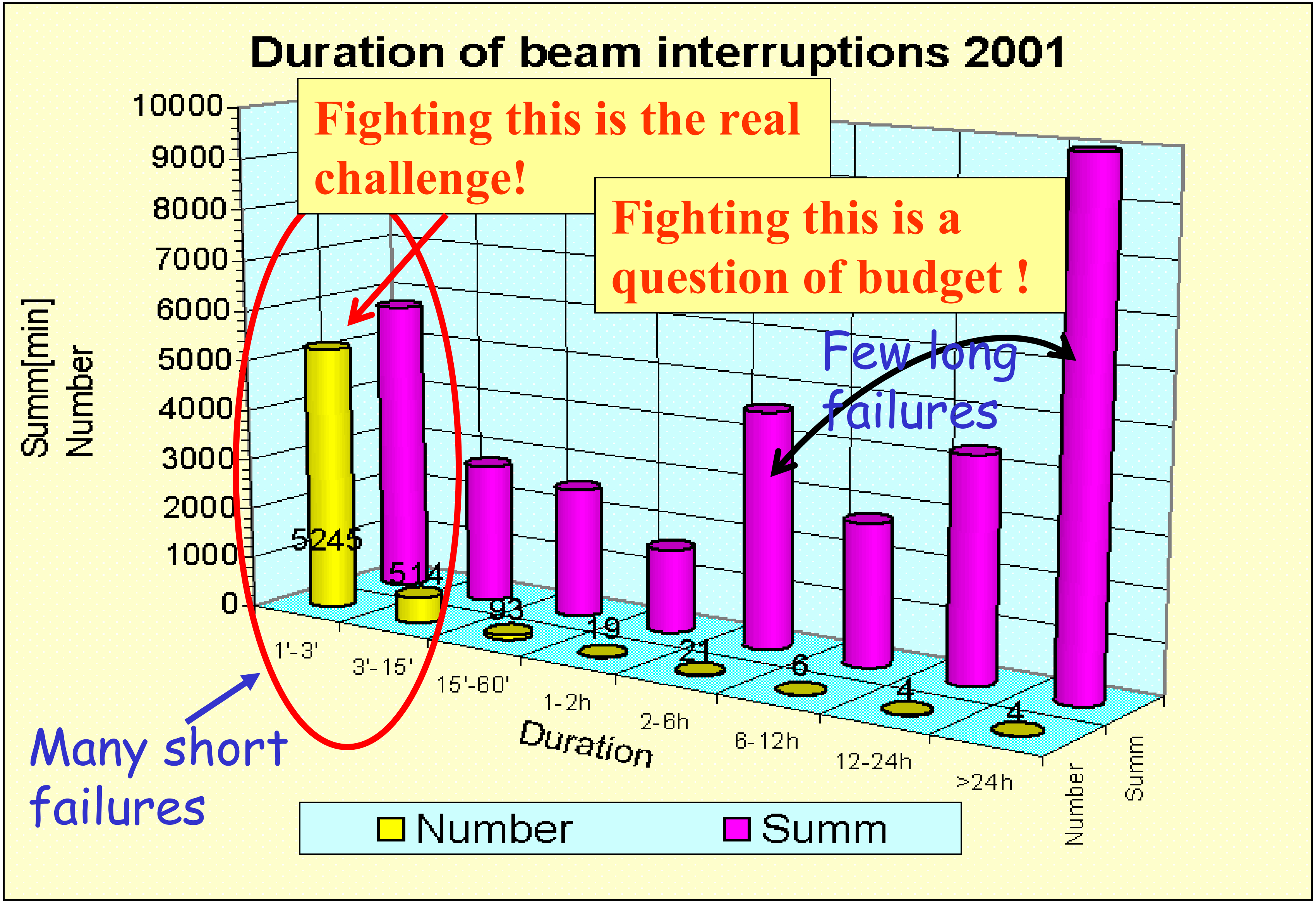
SINQ: a Continuous Spallation Source (Switzerland)

Availability vs beam intensity



Courtesy of P. Schmelzbach/PSI

SINQ: a Continuous Spallation Source (Switzerland)



Fighting this is the real challenge!

Fighting this is a question of budget !

Few long failures

Many short failures

Courtesy of P. Schmelzbach/PSI

SINQ: a Continuous Spallation Source (Switzerland)

Large downtime: A **few events** only

-Cooling: missing redundancy

-Magnets: savings on spare parts, time consuming repairs

-RF: use components until it fails

According to PSI cyclotron experts: **no technological obstacles**. **More a financial problem**:

-Replace 25-year old power supplies (in progress)

-Fully assembled spare parts for magnets (in progress)

-Redundancy of cooling water plant (to be decided)

-Better interchangeability of sub-equipment to decrease MTTR

SINQ: a Continuous Spallation Source (Switzerland)

What about **short trips** / reliability ?

- Short interruptions < 1 min. : 10000 trips per year (1% of the beam time) : 20 s to ramp and recover nominal intensity.

- **Electrostatic elements**: most of the beam trips.
  - critical as the power increases (1.5 -> 1.8 mA).
  - Behaviour of electrostatic elements is far from being understood. R&D is needed (sensitivity to RF-leakage, surface physics, beam halo, …)

(Extensive R&D work is carried out to understand RF arcs caused by microparticle contaminants, e.g: Werner et al.)

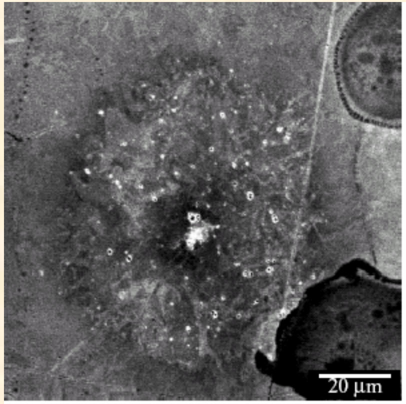


Figure 5: A starburst on electropolished copper.

Investigation of Voltage Breakdown Caused by Microparticles. Werner et al. *PAC 2001 proceedings*

SINQ: a Continuous Spallation Source (Switzerland)

GOAL: reduce RF trips and MDT ! HOW DID THEY DO IT ?

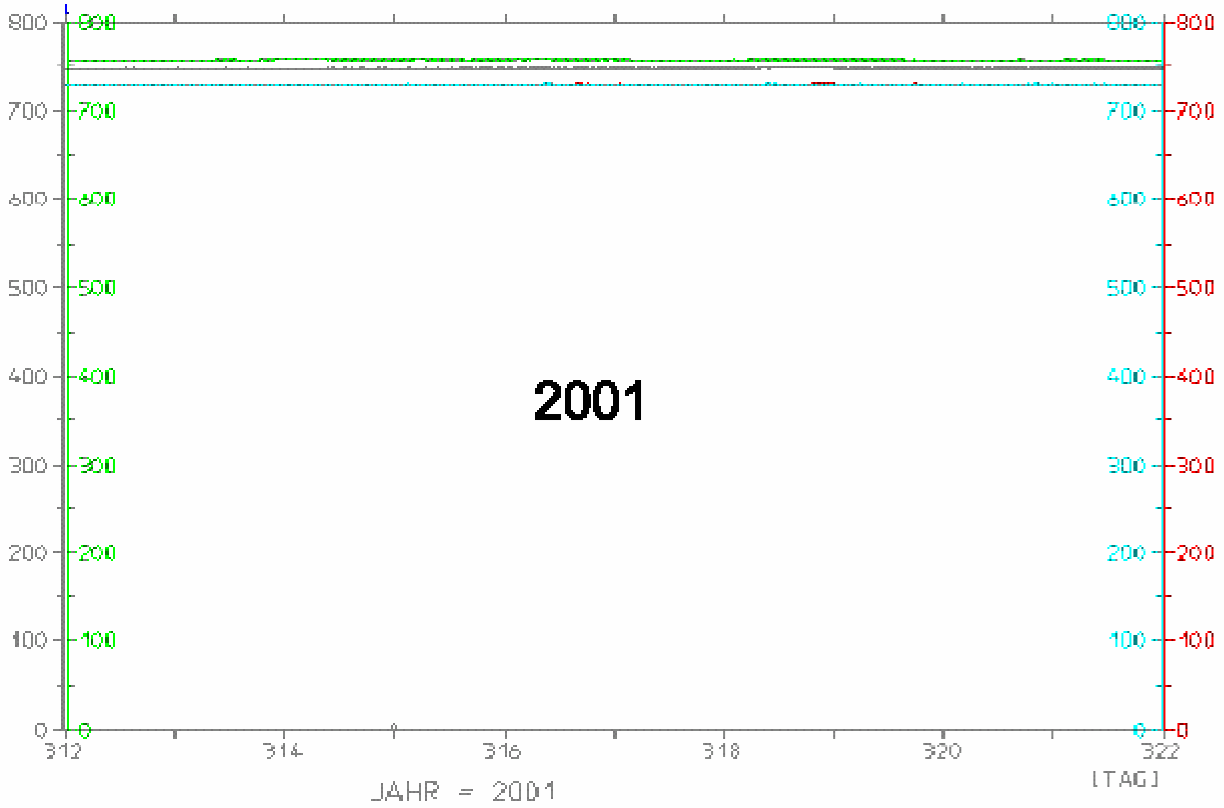
- Better **conditioning** of RF cavities,
- Improvement of **preventive maintenance**:
  - Limited lifetime components (RF tubes are replaced after a pre-determined operation time)
  - 'Unlimited' components periodically inspected, tested.
- DO NOT turn-off beam during self-recovering μ-sparks (< 200 μs) in a cavity
- **Automated ramping procedure** to recover RF power within 5 seconds and full beam after 20 s

WAS IT WORTH MAKING SO MUCH EFFORT ?

Inputs from P. Sigg/PSI

SINQ: a Continuous Spallation Source (Switzerland)

Cavity voltages over a **10- day period**, in 1997 at **1.5 mA** beam current (before new rf-spark control system came into operation), and in Nov. 2001, at **1.8 mA** beam operation.



Note: *Only events (interruptions) of ≥ 1 min.duration are recorded! (in both diagrams)*

Courtesy of P. Sigg/PSI

SINQ: a Continuous Spallation Source (Switzerland)

When the failure is there: reducing the Mean Down Time

- Improved **fault diagnostics and event data logging**
- Ready-to-operate units available (**spare parts**)
- **Design** for fast **interchangeability** of equipment
- **Modular design** at all levels

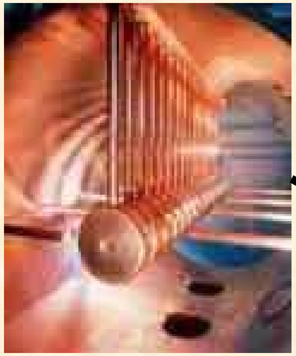
This policy applied at PSI dramatically increased their reliability / availability.

It mainly required ideas, manpower, willingness to improve and RE-design when necessary !

Inputs from P. Sigg/PSI

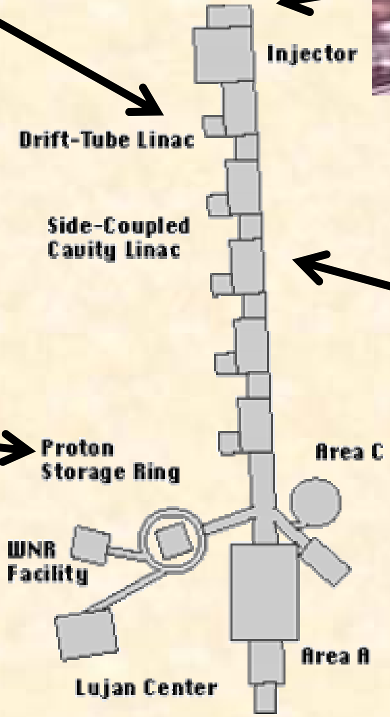
LANSCE: a pulsed Spallation Source (Los Alamos)

1 for H^+, 1 for H^-



100 MeV

750 keV



800 MeV

750 μs pulse→ 0.25 μs

LANSCE: a pulsed Spallation Source (Los Alamos)

Extensive and thorough reliability/failure studies were done at LANSCE (ref: Marcus Eriksson MSc thesis)

Overall statistics:

H^+ beam (seen from Users)

1.6 trip / hour (4655 trips/2870 hours)

General availability: 86 %

H^- beam (seen from Users)

0.8 trip / hour (4020 trips / 5144 hours)

General availability: 85 %

Main problem = repetitive failures (reliability)

LANSCE: a pulsed Spallation Source (Los Alamos)

Weak point: **INJECTORS**

H^+ Injector :70 % of all trips

90 % of H^+ Injector trips were < 1 minute !

H^- Injector : 26 % of all trips

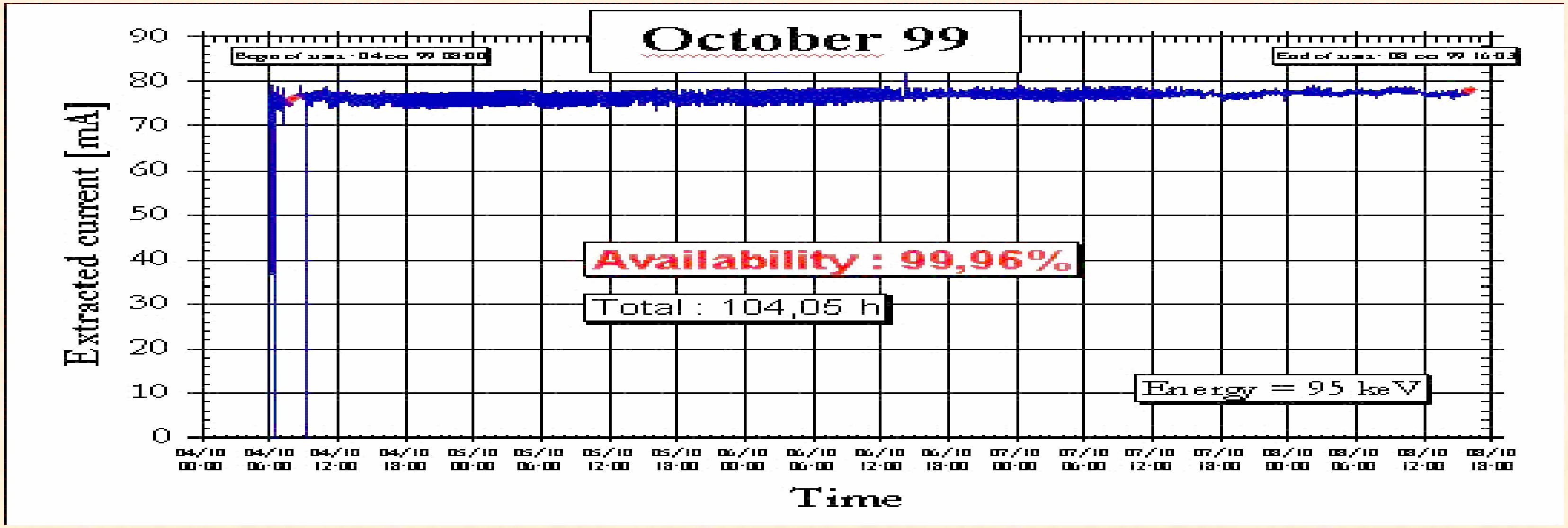
40 % of H^-Injector trips were < 1 minute !

BUT, these are Cockroft-Walton type injectors. This can NOT be extrapolated for future accelerators! ***WHY ?***

Nowadays, many ion sources have been designed with the purpose of having a high rate of reliability. Example: SILHI source on IPHI project (CEA)

Courtesy of P-Y Beauvais (CEA)

Parameters	Oct. 99
Energy (keV)	95
Intensity (mA)	75
Duration (h.)	104
Beam off number	1
MTBF (h)	-
MTTR (mn)	2.5
Availability (%)	99.96



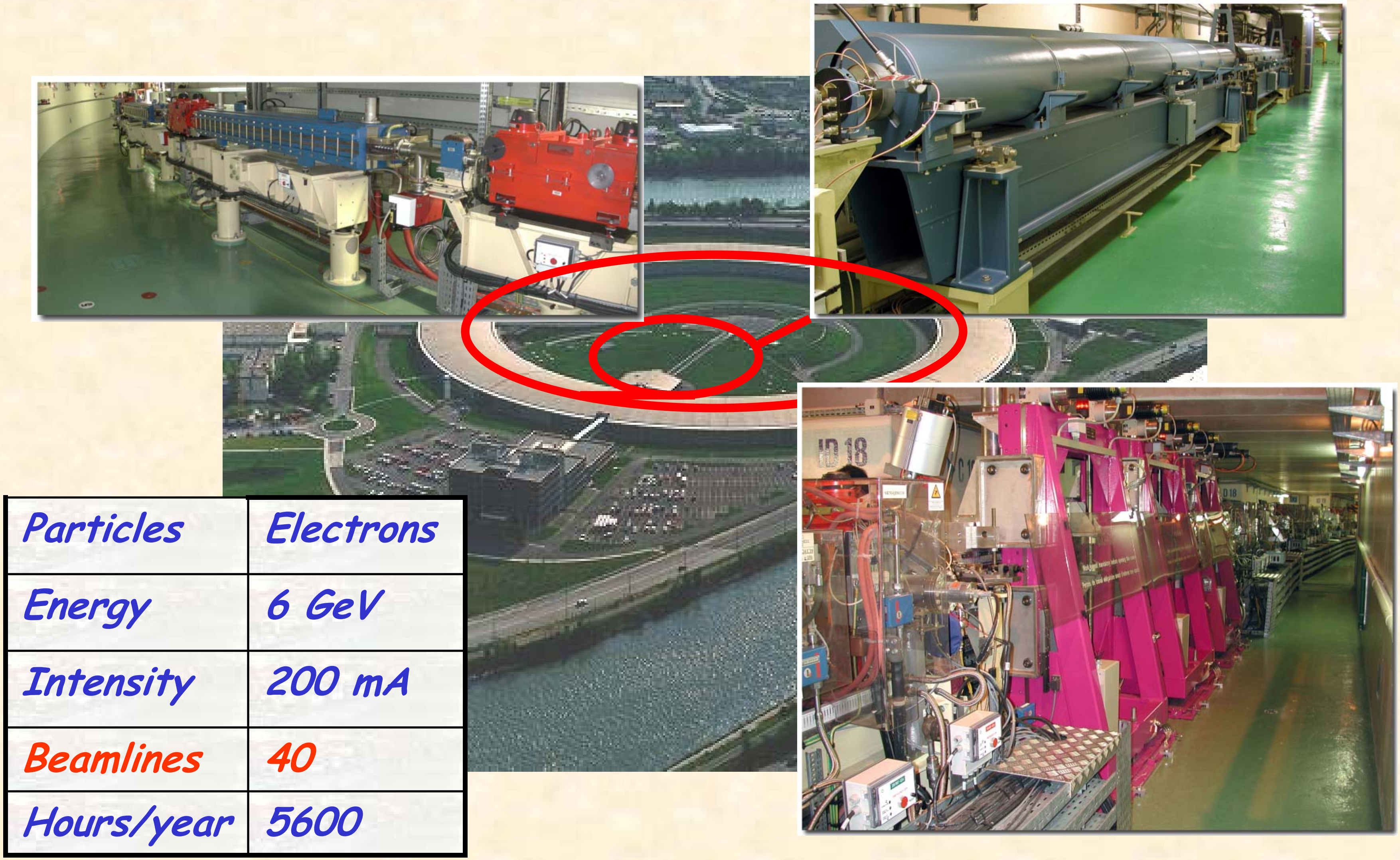
LANSCE: a pulsed Spallation Source (Los Alamos)

PRELIMINARY CONCLUSION

Failure database of existing facilities are of primary importance to understand and correct weakpoints.

HOWEVER, they must NOT be extrapolated 'blindly' for future machines ! Technologies are evolving …

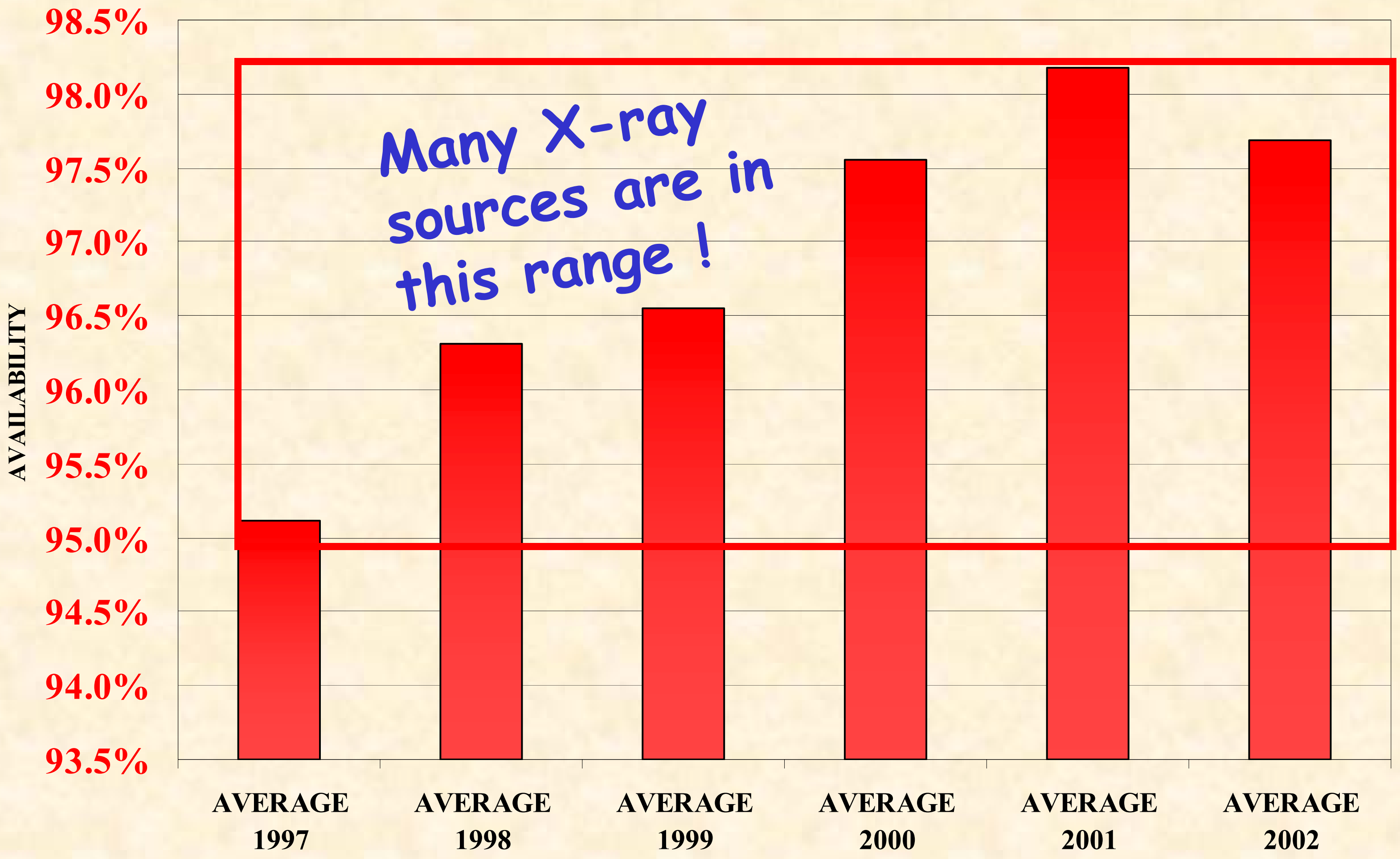
The ESRF: a third generation X-ray source



Particles	*Electrons*
Energy	*6 GeV*
Intensity	*200 mA*
Beamlines	*40*
Hours/year	*5600*

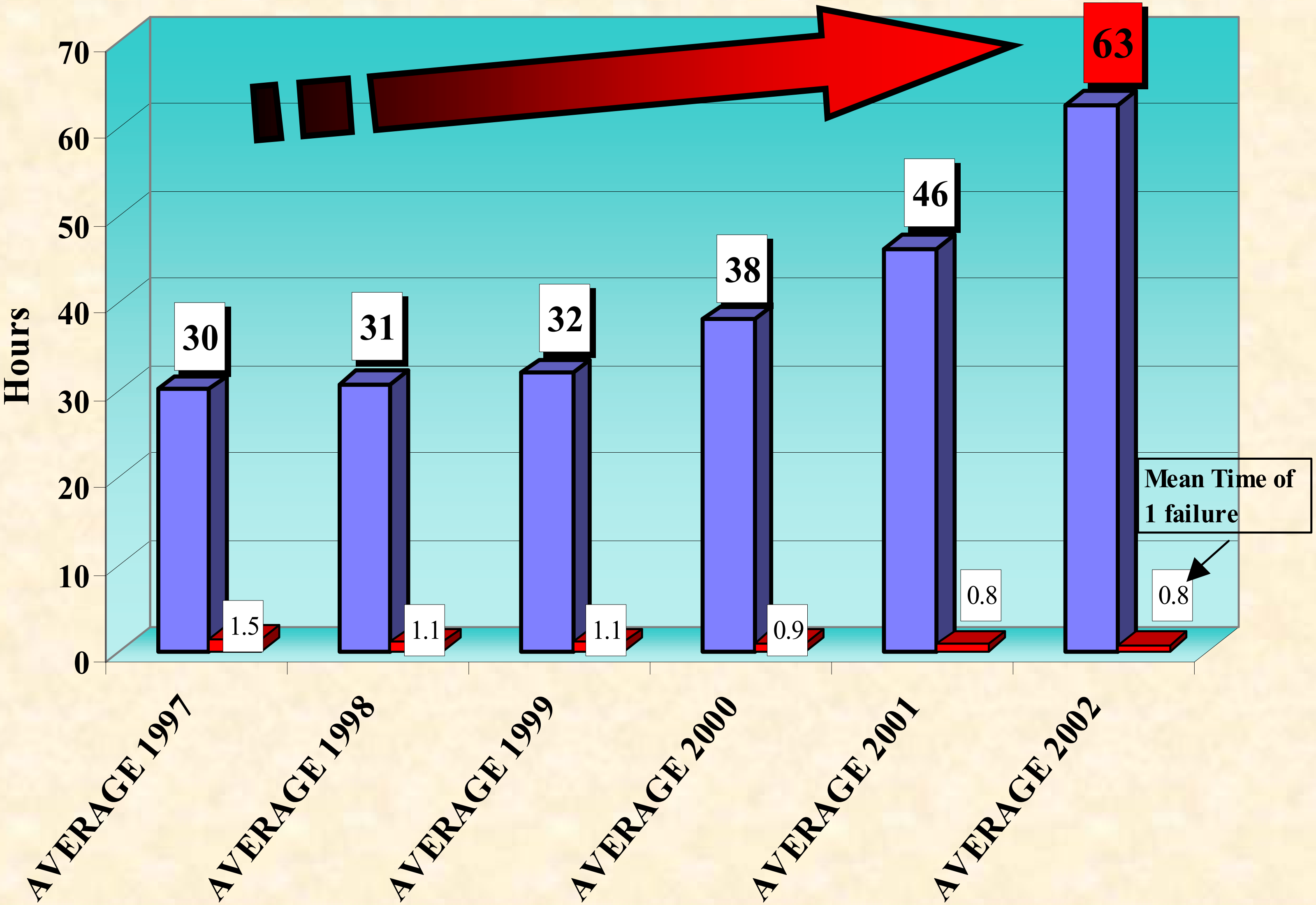
The ESRF: a third generation X-ray source

Storage Ring availability



Many X-ray sources are in this range !

MTBF and Mean Down Time over the years

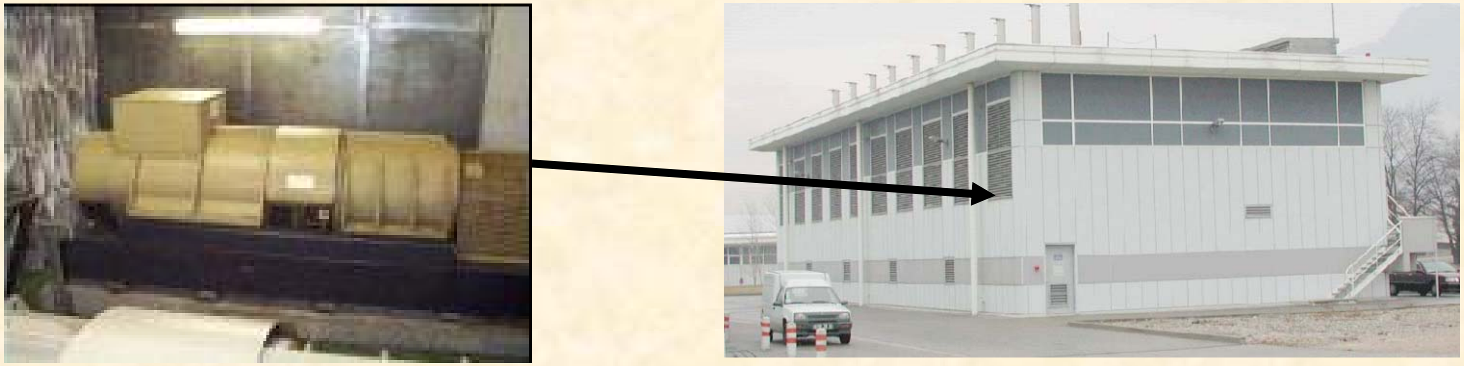


The ESRF: a third generation X-ray source

All failures are recorded, analysed → solutions and strategies are proposed. Here are a few examples:

1. Electrical mains drops (mainly due to storms) are detected and compensated for by 10 Diesel engines (total = 10 MVA)

10 X



Courtesy of JF Bouteille

COSTS

Investment: 6 M€

Maintenance: 60 k€ / year

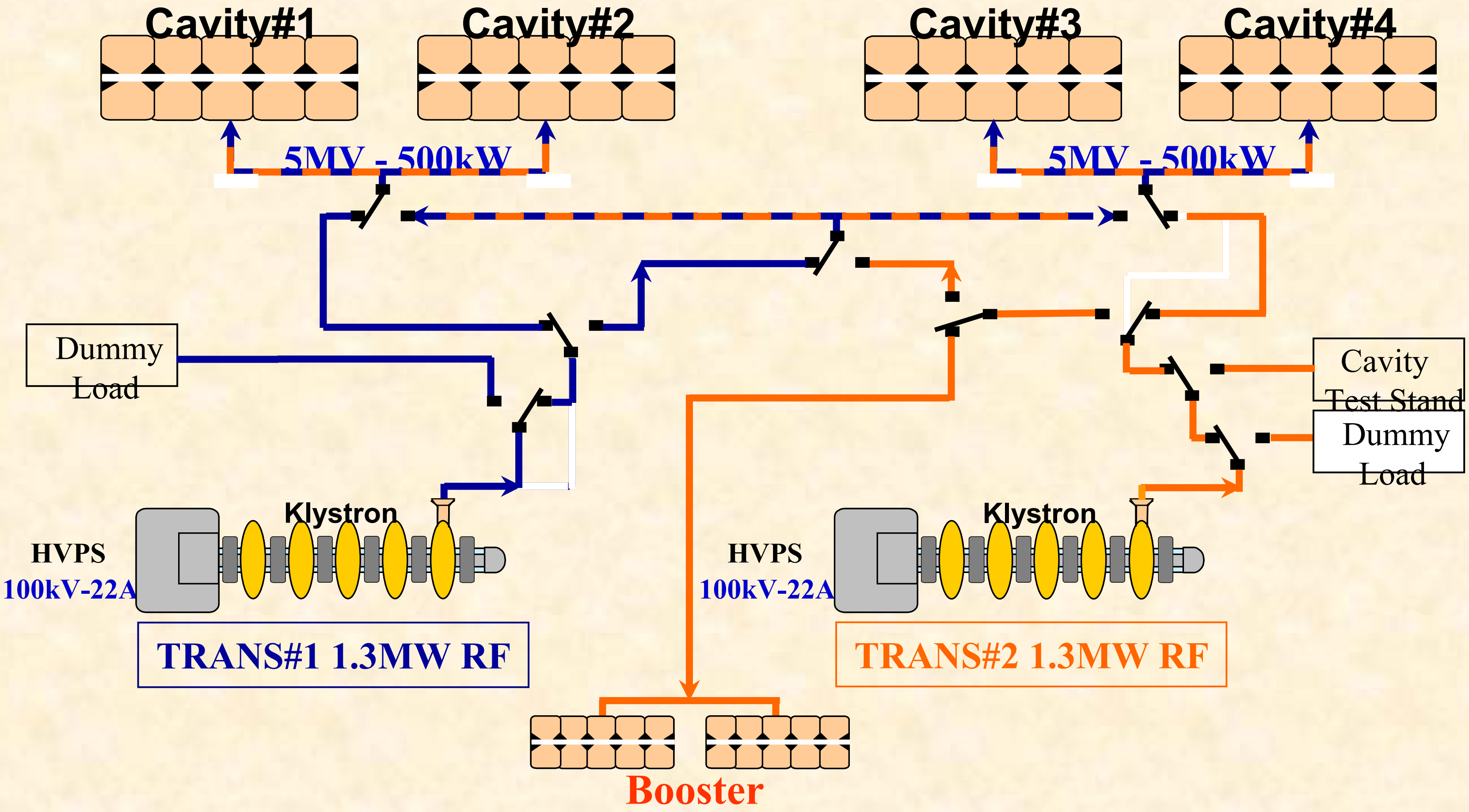
RESULTS

60 severe drops/year compensated by starting the Diesel engines

BOTH REPETITIVE AND LONG TRIPS NOW AVOIDED !

The ESRF: a third generation X-ray source

2. Complete redundancy of RF system



+ third klystron installed on a new third pair of cavities → decrease RF power per cavity window

Courtesy of JM Mercier

The ESRF: a third generation X-ray source

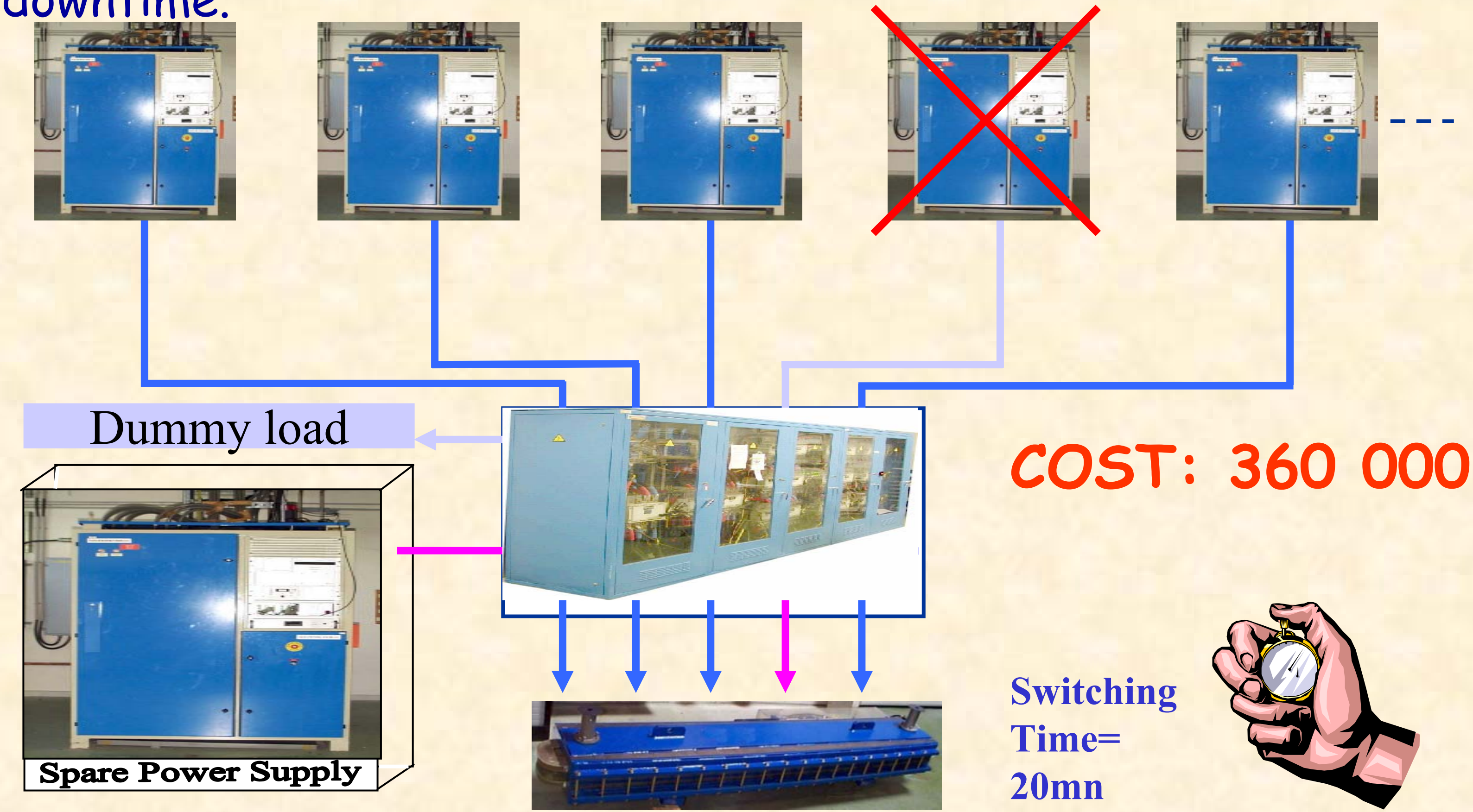
RESULTS

	1998	1999	2000	2001
Number of RF trips	120	102	78	53
Time lost due to RF (h)	70	36	33	27

The ESRF: a third generation X-ray source

3. THE POWER SUPPLIES SWITCHING BOARD:

An efficient system to minimize power supplies failure downtime.



COST: 360 000 €

Switching Time= 20mn

1200 V - 800 A

Courtesy of JM KOCH

The ESRF: a third generation X-ray source

- Fighting all failures, long and repetitive, is a top-priority for dedicated X-ray source

- Recording, analysing failures and defining strategies to make them disappear is almost a FULL-TIME job !

- Long failures: AVOIDABLE but this costs (a lot of) money (redundancy). Origins are generally quickly and well identified. Must be taken into account during the design stage.

- Short failures: AVOIDABLE but this costs manpower, time, R&D because origins are generally long and difficult to identify.

- Strategies to avoid human mistakes remain a challenge! (the fifth cause for time lost at ESRF in 2001 …)

A BRIEF FUTURE OF ACCELERATOR RELIABILITY…

ACCELERATOR DRIVEN SYSTEM →

-SPALLATION SOURCES

-NUCLEAR WASTE TRANSMUTATION

-SUB-CRITICAL NUCLEAR REACTOR !

5th June 2002

Typical HPPA parameters:

800 MeV – 10 mA proton

2015: Feasibility demonstration

< 10 TRIPS/YEAR

(trips < 100 ms can be accomodated but detrimental to the target)

2050

Industrial applications

… and even 2-3 / year for an industrial accelerator !

IS IT REALISTIC ? WHAT IS THE PRICE TO PAY ?

Dream Machines: the price to pay, the efforts to make

1. AVOID LONG TRIPS: generally a question of money (redundancy)

- Diesel engines : 6 M€ for 10 MW + 60 k€/year
- Power supply switching board: 360 k€
- RF redundancy , water pumps redundancy, Control system redundancy, etc, etc
- Preventive maintenance: Frequent shutdowns must be foreseen

Excellent cost study made by R. Ferdinand et al. on the ESS Linac:

A conservative and reliable Linac for ESS costs 50 % more than a 'nominal' design: 157 M€ + 77 M€ reliability = 234 M€

The yearly operation cost is increased by about 1.3M€

Dream Machines: the price to pay, the efforts to make

•Cryogenic plants: should we be afraid ?

Most sensitive elements = turbines:

At low working T°, impurity = solid pellet → can damage the turbine wheel → important point for the turbine reliability is the impurities level control in the helium flow

Cryogeny experts: ~ 1 year is necessary to improve the cryoplant system reliability ('childhood diseases'), train Operators, etc. Then, **reliability is excellent : > 99 % !**

KEK: 137000 hours experience: reliability = 99.2 % !

Fermilab: 76000 hours experience: reliability = 99.5 % !

CERN: 120000 hours experience: 99.3 % !

BUT … Sub-component REDUNDANCY is THE key point !!

Thank you to C. Commeaux for his inputs

Dream Machines: the price to pay, the efforts to make

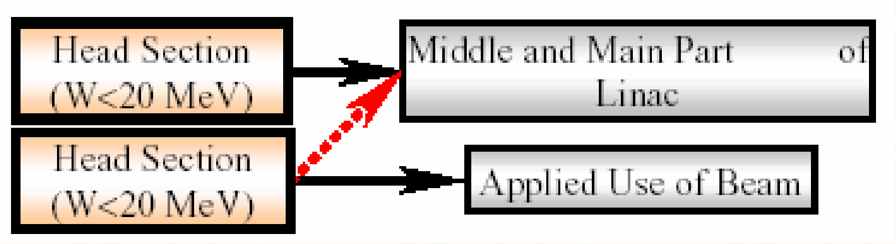
2. Avoid REPETITIVE TRIPS:

Lot of **REALISTIC R&D** in progress and showing promising results:

- Ion source reliability (SILHI, CDPADS in China, others)

  > 100 hours run @ high intensity without single failure !

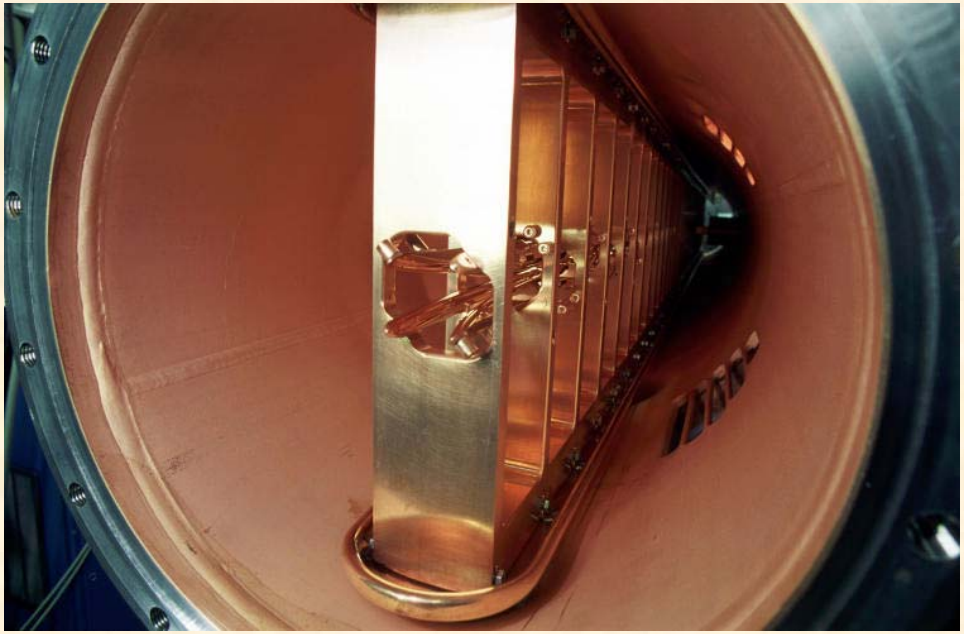
- Realistic schemes for Active redundant sections from ADS Linac systems. An active spare section can take over a stopped section within 50 msec !(Work of Kozodaev et al.)



Kozodaev et al.

- RFQ design optimization

Now a standard for low-energy ion injectors

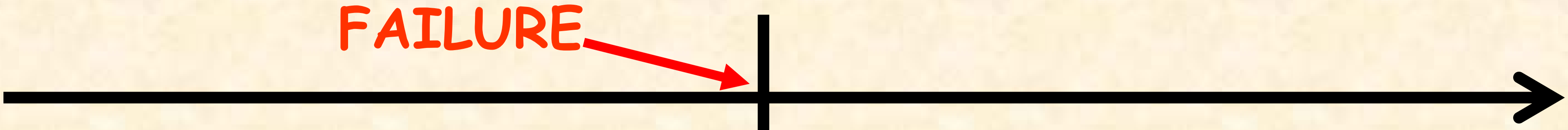


-Vane shape optimization (<->minimization of electric field)

-High pumping capacity → minimisation of bursts and hence sparks

→ **Beam interruption probability is minimized**

A CHAIN IS AS STRONG AS ITS WEAKEST LINK !



-Design optimization (margin !)

-Preventive Maintenance

-Experience from other Institutes

-Realistic Operation Schedule

-Redundance

-Avoid human mistake with automation when necessary

-FAULT DIAGNOSTICS !!

-Rigorous Spare part Policy

-Experts on standby 24 hours/day ready to intervene

-Operator's training

-Fast interchangeability of components (<- design …)

-Repair procedures

CONCLUSION

- Reliability / availability is now a priority for particle accelerator designers: great progress !
- Many existing devices ARE already reliable !
- R&D for future ADS is difficult BUT REALISTIC. Promising results have ALREADY been seen
- Parallel efforts MUST be done in the design process: spare parts, training, procedure, etc

Achieving « Dream Machines » is no longer a dream but will require the best expertise for all links in the design chain