SNS Linac Reliability Model (MAX Task 4.2-Myrrha Accelerator eXperiment)

Technology and Components of Accelerator-driven Systems - Second International Workshop

21-23 May 2013 -Nantes, France

Adrian Pitigoi, Pedro Fernández - EA

1. SNS Linac Modeling
2. SNS Model – Input Data
3. Modeling Methodology
4. SNS Fault Tree Development
5. SNS Systems - Reliability Analysis
   SNS RS - Model and results evaluation
   SNS Logbook Data
6. Conclusions
7. Next Step (MAX Task 4.4)

1. SNS Linac Modeling

❑ **WP 4 Task 4.2 Objective - Reliability model of SNS Linac accelerator**

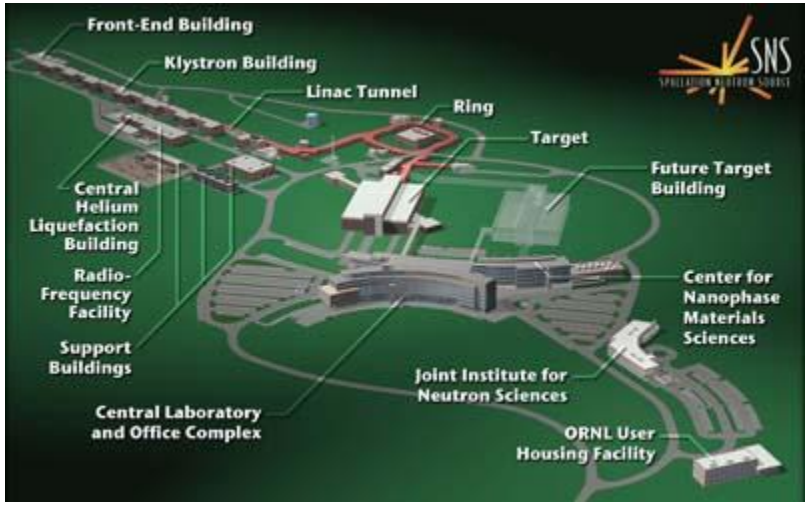
- **Feedback** on actual **SNS reliability performance**, in order to develop a **reliability modeling tool** for MAX project

❑ **Task 4.2 Activities:**

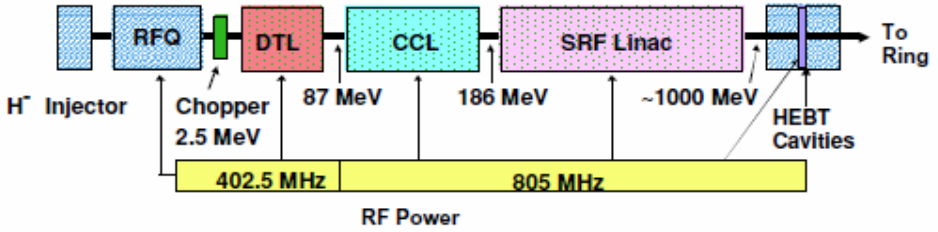
- **Selection of the accelerator** to be used for modeling **(SNS)**
- SNS Design & Reliability **data collection**
- Development of **SNS Linac RS reliability model**
- Performing **reliability analysis** of SNS Linac systems,

❑ **Task 4.2 Targets:**

- **Evaluate the SNS Linac model** (model results vs. SNS operational data)
- **Conclusions** and recommendations on **optimization, increasing reliability.**



Layout of the SNS Linac

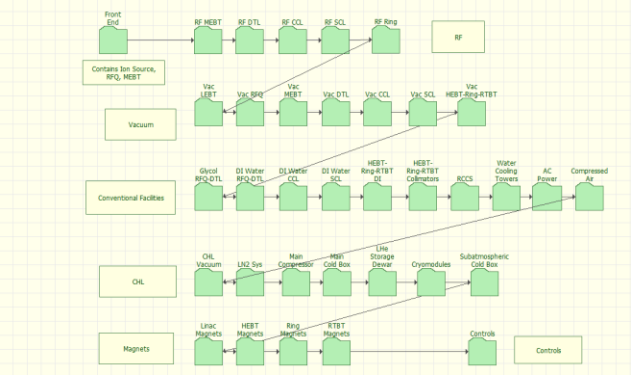


2. SNS Model - INPUT DATA

- **SNS Design Data**
  - SNS Accelerator overall structure (main and auxiliary systems); system interfaces
  - Systems components/interconnection
  - Number of components (by type)
  - Degree of redundancy

Data Sources:

- SNS RAMI Static Model
- SNS BlockSim model (Reliasoft)

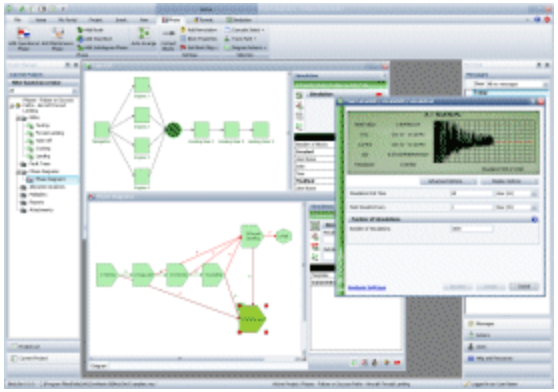


SNS BlockSim Model

- **SNS Systems and Functions**
  - SNS Parameters
  - Systems and components
  - System functions
  - Systems functional interdependencies

Data Sources:

- SNS website (http://neutrons.ornl.gov/facilities/SNS/): ¨How SNS works¨ - http://neutrons.ornl.gov/facilities/SNS/works.shtml;
- SNS Parameters (doc no. SNS 100000000-PL001R13) (http://neutrons.ornl.gov/media/pubs/pdf/sns_parameters_list_june05.pdf)
- SNS Design Control Documents (DCD)



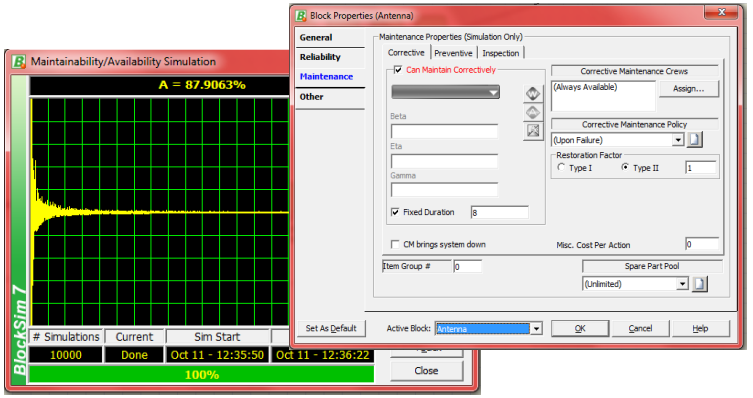
2. SNS Model - INPUT DATA

- **SNS Reliability Data**
  - Number of components (by type)
  - Degree of redundancy
  - Failure data: λ=1/MTTF; MTTR

    (λ – Failure rate; MTTF-Main Time To Failure; MTTR-Main Time To Repair)

Data Sources:

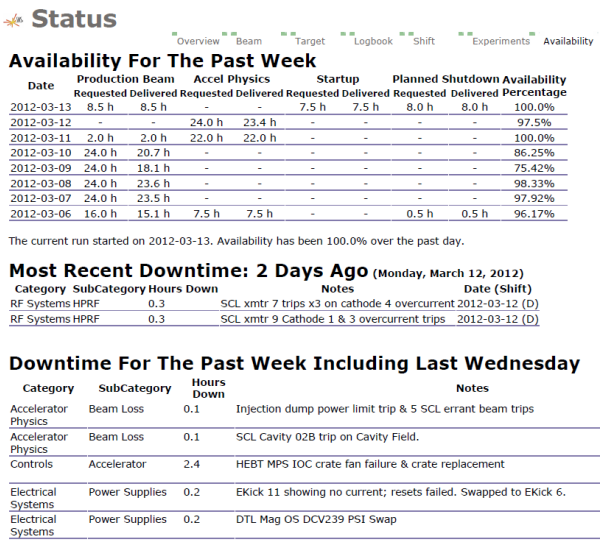
- RAMI Static Model
- SNS BlockSim detailed model



- **SNS Operating Status**
  - Component failures - cause, type of component, time to repair, etc.
  - Availability data (component failures causing accelerator trips: cause, component and system concerned, duration of trip)

Data Sources:

- SNS Operation Data collection (http://status.sns.ornl.gov/beam.jsp)



Status

Overview | Beam | Target | Logbook | Shift | Experiments | Availability

Availability For The Past Week

Date	Production Beam Requested	Production Beam Delivered	Accel Physics Requested	Accel Physics Delivered	Startup Requested	Startup Delivered	Planned Shutdown Requested	Planned Shutdown Delivered	Availability Percentage
2012-03-13	8.5 h	8.5 h	-	-	7.5 h	7.5 h	8.0 h	8.0 h	100.0%
2012-03-12	-	-	24.0 h	23.4 h	-	-	-	-	97.5%
2012-03-11	2.0 h	2.0 h	22.0 h	22.0 h	-	-	-	-	100.0%
2012-03-10	24.0 h	20.7 h	-	-	-	-	-	-	86.25%
2012-03-09	24.0 h	18.1 h	-	-	-	-	-	-	75.42%
2012-03-08	24.0 h	23.6 h	-	-	-	-	-	-	98.33%
2012-03-07	24.0 h	23.5 h	-	-	-	-	-	-	97.92%
2012-03-06	16.0 h	15.1 h	7.5 h	7.5 h	-	-	0.5 h	0.5 h	96.17%

The current run started on 2012-03-13. Availability has been 100.0% over the past day.

Most Recent Downtime: 2 Days Ago (Monday, March 12, 2012)

Category	SubCategory	Hours Down	Notes	Date (Shift)
RF Systems	HPRF	0.3	SCL xmtr 7 trips x3 on cathode 4 overcurrent	2012-03-12 (D)
RF Systems	HPRF	0.3	SCL xmtr 9 Cathode 1 & 3 overcurrent trips	2012-03-12 (D)

Downtime For The Past Week Including Last Wednesday

Category	SubCategory	Hours Down	Notes
Accelerator Physics	Beam Loss	0.1	Injection dump power limit trip & 5 SCL errant beam trips
Accelerator Physics	Beam Loss	0.1	SCL Cavity 02B trip on Cavity Field.
Controls	Accelerator	2.4	HEBT MPS IOC crate fan failure & crate replacement
Electrical Systems	Power Supplies	0.2	EKick 11 showing no current; resets failed. Swapped to EKick 6.
Electrical Systems	Power Supplies	0.2	DTL Mag OS DCV239 PSI Swap

http://status.sns.ornl.gov/beam.jsp

3. Modeling Methodology

❑ General Assumptions

- SNS systems/components not modeled – **Ring - RTBT, stripper foil**, etc. (considered as not relevant for Max project purposes)

- **Risk Spectrum Type 1** – **Repairable components** reliability model (continuously monitored) – Type 1 reliability model - modeling all SNS Linac components

- ¨**Mean Unavailability**¨ type of calculation is used to obtain the unavailability values of the basic events; (the **long-term average unavailability Q** is calculated for each basic event)

a) The 1,000-foot SNS linear accelerator is made up of three different types of accelerators.

b) The SNS ring intensifies the high-speed ion beam and shoots it at the mercury target 60 times a second (60 Hz).

c) Target

3. Modeling Methodology

General Assumptions

- **Continuously monitored repairable component**

  RSType 1 reliability model has been considered for modeling all SNS Linac components failing behavior.

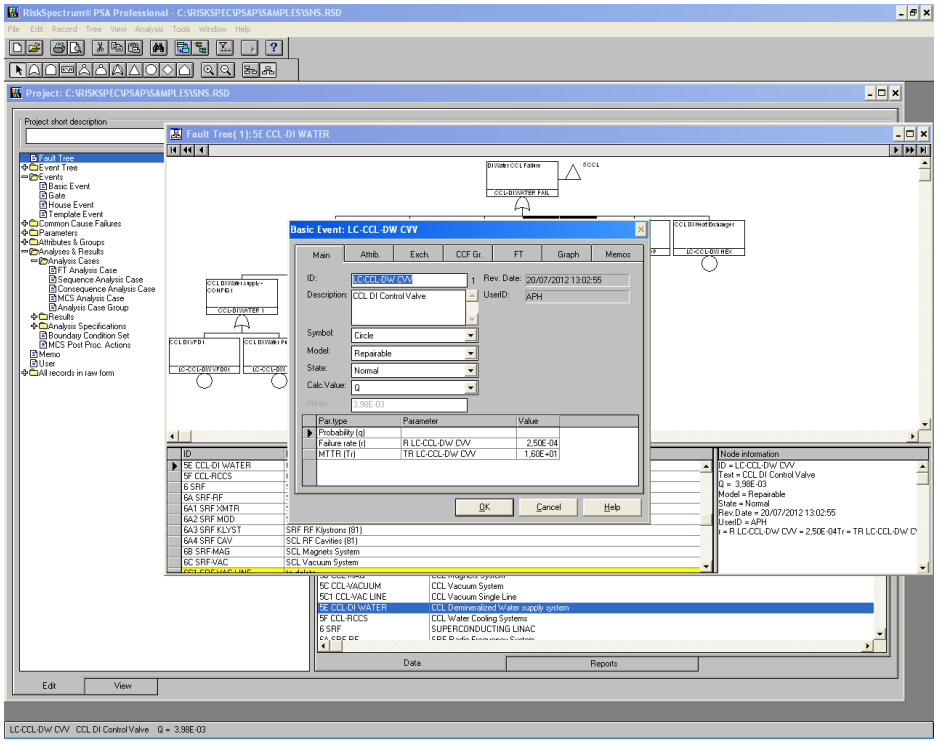
  - Failure/Repair processes – exponential distributions; failure/repair rates ct.
  - It is assumed q=0

$$Q(t) = q\,e^{-\mu t} + \left(\frac{\lambda}{\lambda+\mu}\right)\left(1 - e^{-(\lambda+\mu)t}\right) \qquad Q_{mean} = \frac{\lambda}{\lambda+\mu}$$

(λ=1/MTTF (failure rate); μ=1/MTTR (repair rate))
MTTF;MTTR data – BlockSim Model data

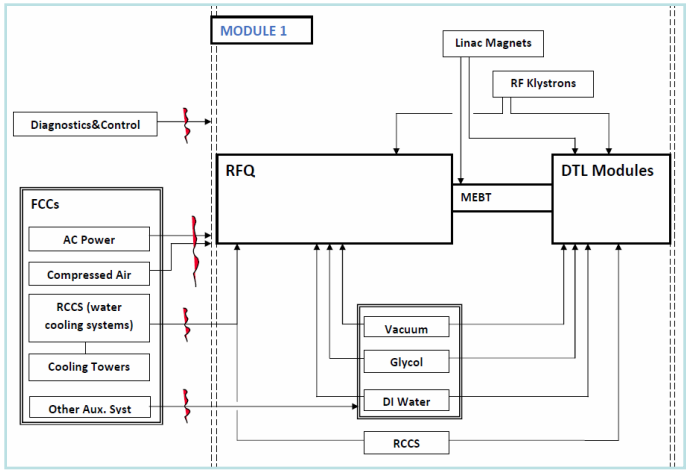
- **¨Mean Unavailability¨ type of calculation** is used for calculating basic events availabilities:

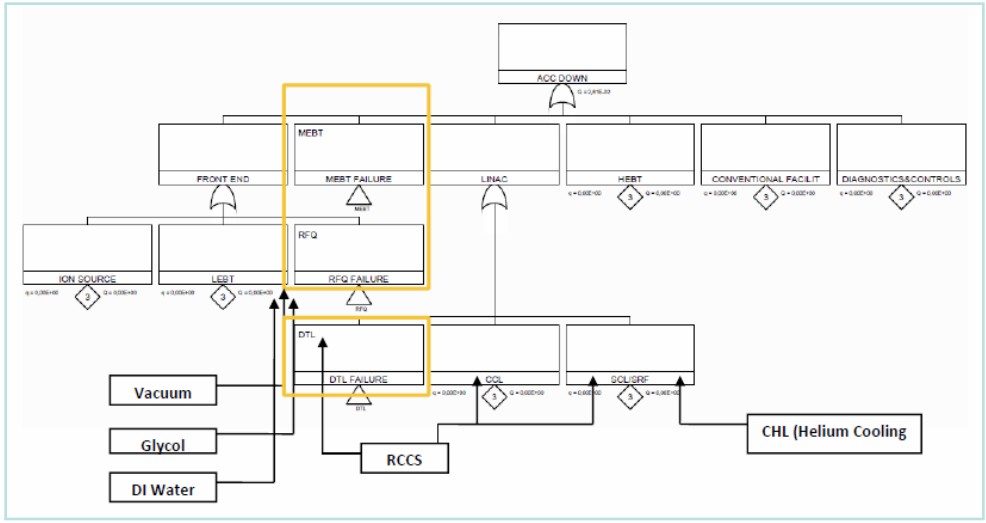
$$Q=\lambda/(\lambda+\mu)$$



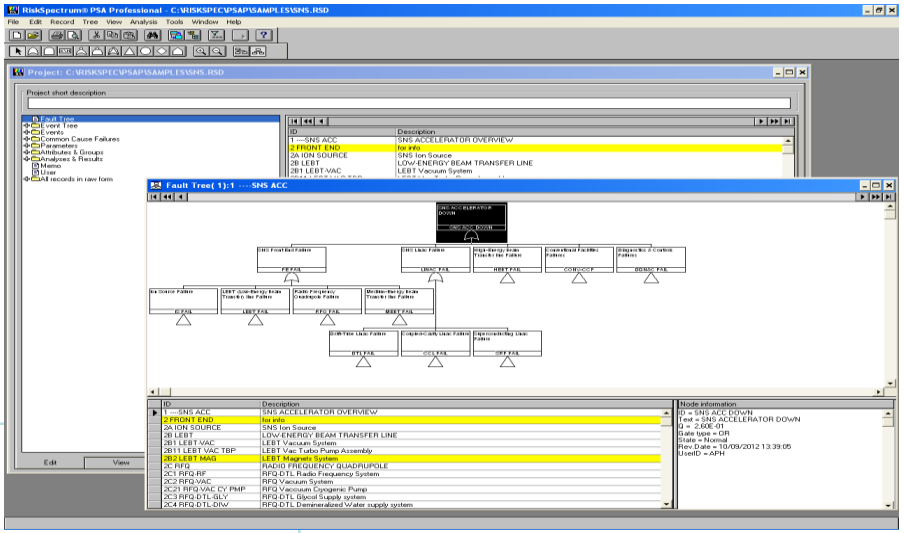
4. SNS Reliability Model - Fault Tree Model

- **SNS Module 1**- first modeling step: RFQ + MEBT + DTL
  - Gradual development of the SNS Linac model
  - In-depth understanding of the SNS design and functioning for an accurate model.

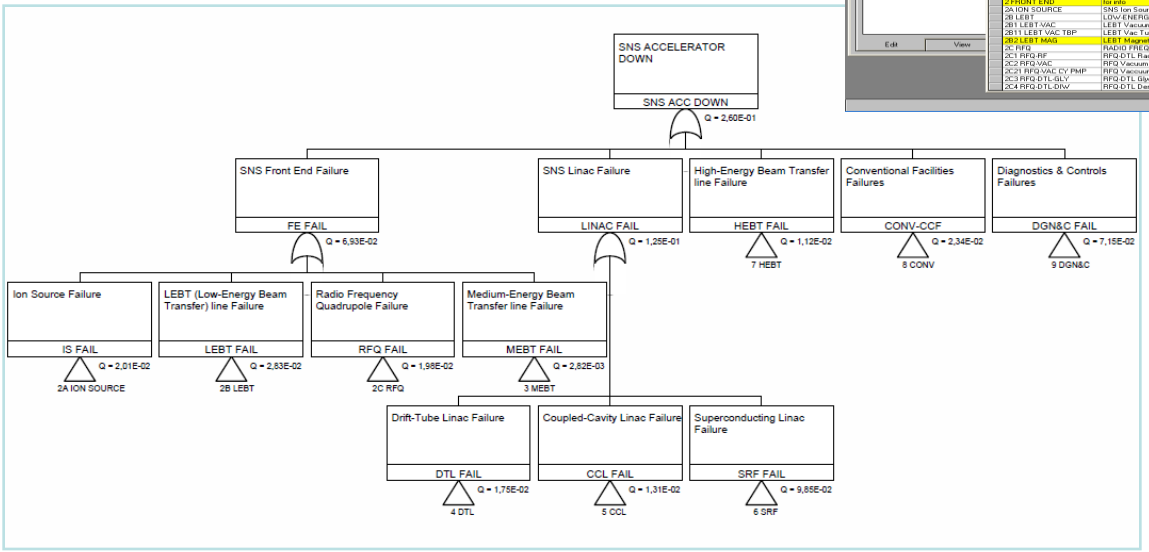




4. SNS Reliability Model - Fault Tree Model



➢ **SNS Fault Tree (complete model)** - graphical representation of the SNS systems functional structure describing undesired events (“ system failures") and their causes.

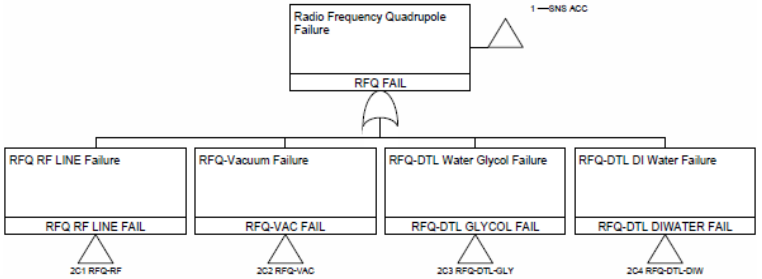


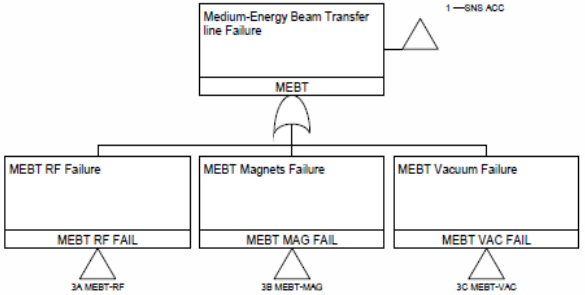
➢ The Fault tree – logical gates and basic events.

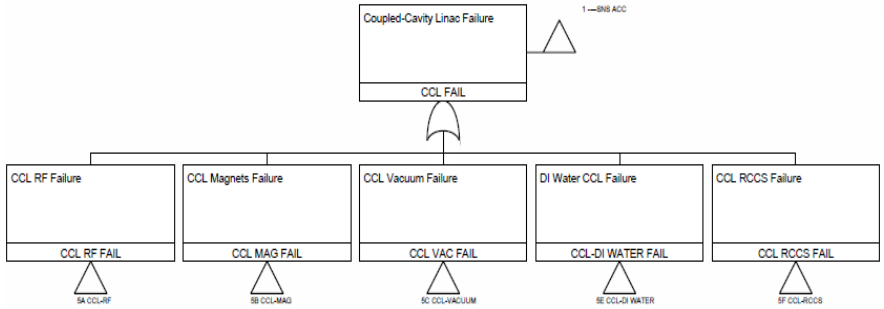
➢ A fault tree - subdivided between several fault tree pages (bound together using transfer gates).

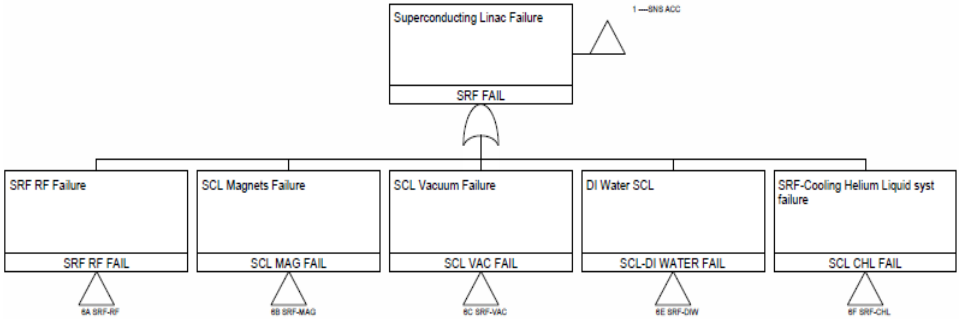
4. Modeling the SNS Linac

- **SNS Linac Fault Tree Structure** - Main levels of the fault trees - major parts of the SNS accelerator (Ion Source, LEBT, RFQ, MEBT, DTL-CCL-SCL, HEBT, CONV - auxiliary systems)



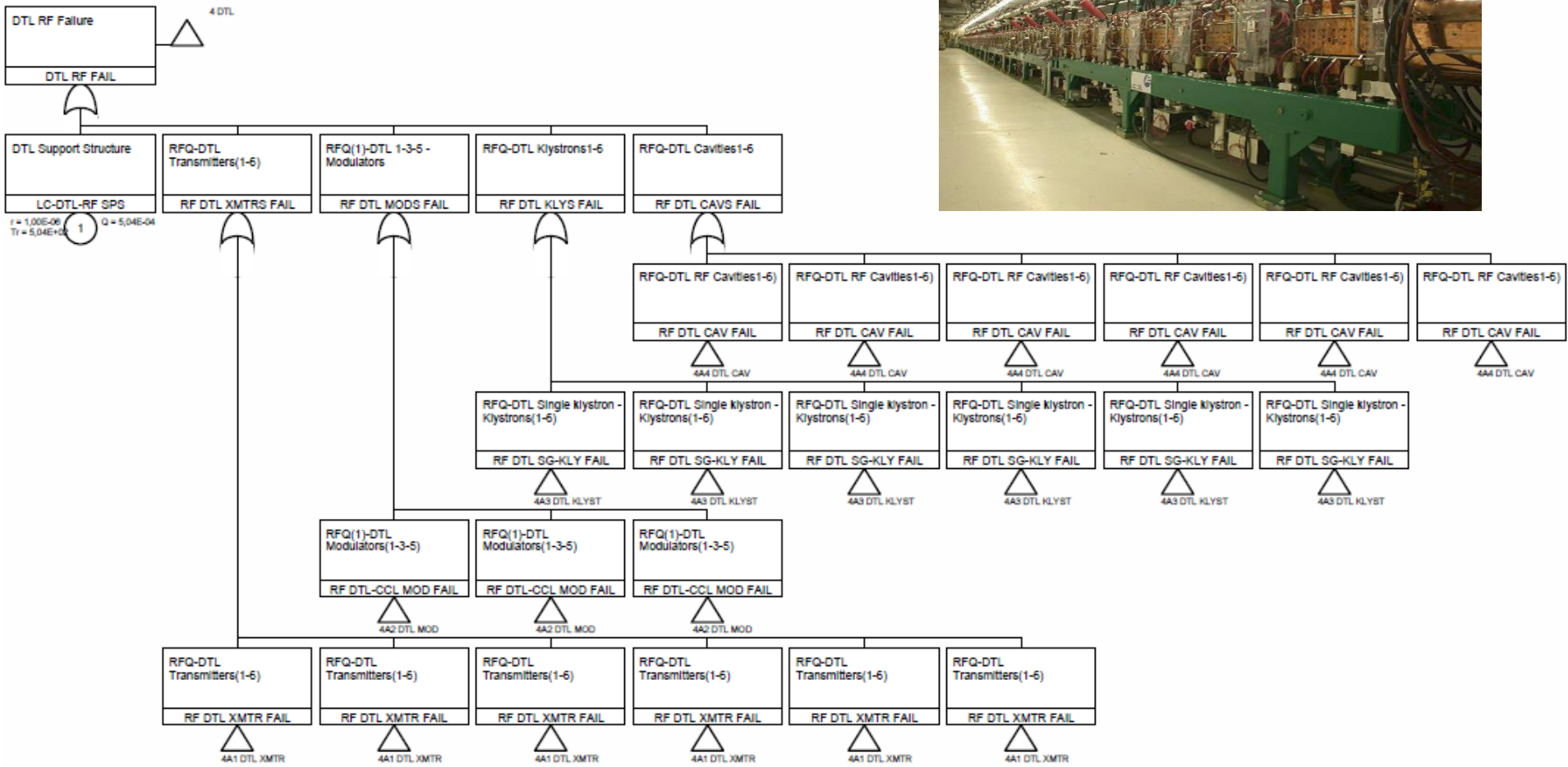






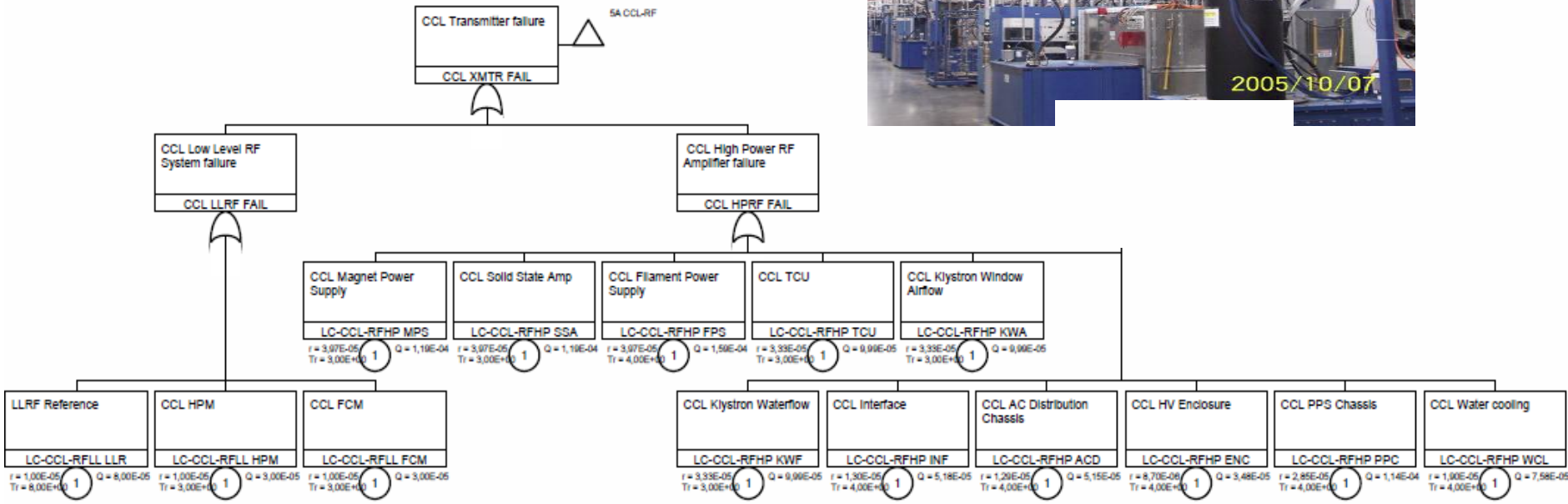
4. Modeling the SNS Linac

- **DTL RF Fault Tree Structure**

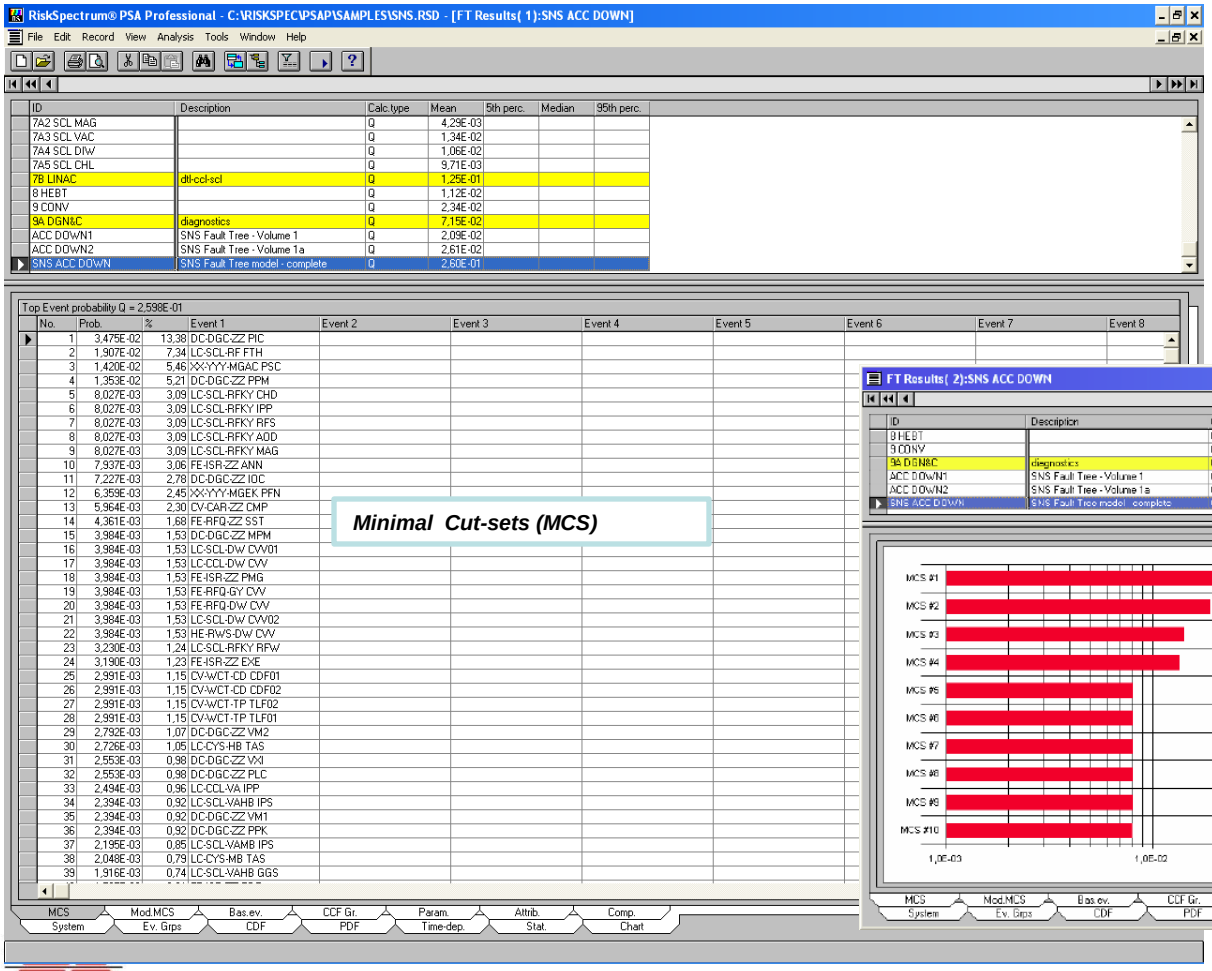


4. Modeling the SNS Linac

- **CCL Transmitter Fault Tree Structure**



5. SNS Systems - Reliability Analysis Results



- **Analysis Case – Results**

  Q = 2.60E-01 = 0.26; Q = 26 %

  A = 1 - Q = 73 % (the limit Availability – Mean Availability)

5. SNS Systems - Reliability Analysis Results

Minimal Cut-sets (MCS)

Minimal Cutsets

Top Event probability Q = 2,598E-01

No.	Prob.	%	Q	Event	Description
1	3,475E-02	13,38	3,475E-02	DC-DGC-ZZ PIC	EPIC Modules -900series
2	1,907E-02	7,34	1,907E-02	LC-SCL-RF FTH	SCL RF Feedthroughs (81):(12+12+12+6+6+
3	1,420E-02	5,46	1,420E-02	XX-YYY-MGAC PSC	Arc PSC - 36 series
4	1,353E-02	5,21	1,353E-02	DC-DGC-ZZ PPM	PPS Modules -343series
5	8,027E-03	3,09	8,027E-03	LC-SCL-RFKY CHD	SCL Cathode (x81)
6	8,027E-03	3,09	8,027E-03	LC-SCL-RFKY IPP	SCL Ion Pump (x81)
7	8,027E-03	3,09	8,027E-03	LC-SCL-RFKY RFS	SCL RF Structure (x81)
8	8,027E-03	3,09	8,027E-03	LC-SCL-RFKY AOD	SCL Anode (x81)
9	8,027E-03	3,09	8,027E-03	LC-SCL-RFKY MAG	SCL Magnet (x81)
10	7,937E-03	3,06	7,937E-03	FE-ISR-ZZ ANN	ISR Antenna
11	7,227E-03	2,78	7,227E-03	DC-DGC-ZZ IOC	IOCs -182series
12	6,359E-03	2,45	6,359E-03	XX-YYY-MGEK PFN	PFN - 10 series
13	5,964E-03	2,30	5,964E-03	CV-CAR-ZZ CMP	CAR Compressor
14	4,361E-03	1,68	4,361E-03	FE-RFQ-ZZ SST	RFQ Support Structure
15	3,984E-03	1,53	3,984E-03	DC-DGC-ZZ MPM	MPS Modules -100series
16	3,984E-03	1,53	3,984E-03	LC-SCL-DW CVV01	SCL DI Control Valve 1
17	3,984E-03	1,53	3,984E-03	LC-CCL-DW CVV	CCL DI Control Valve
18	3,984E-03	1,53	3,984E-03	FE-ISR-ZZ PMG	ISR Permanent Magnets - 50 series
19	3,984E-03	1,53	3,984E-03	FE-RFQ-GY CVV	Glycol Control Valve
20	3,984E-03	1,53	3,984E-03	FE-RFQ-DW CVV	DTL DI Control Valve
21	3,984E-03	1,53	3,984E-03	LC-SCL-DW CVV02	SCL DI Control Valve 2
22	3,984E-03	1,53	3,984E-03	HE-RWS-DW CVV	HEBT RWS - RF DI Control Valve
23	3,230E-03	1,24	3,230E-03	LC-SCL-RFKY RFW	SCL RF Window (x81)
24	3,190E-03	1,23	3,190E-03	FE-ISR-ZZ EXE	ISR Extractor Electrode - 2 series
25	2,991E-03	1,15	2,991E-03	CV-WCT-CD CDF01	Condenser Fan 1
26	2,991E-03	1,15	2,991E-03	CV-WCT-CD CDF02	Condenser Fan 2

- **Analysis Case – Results**

  Q = 2.60E-01 = 0.26; Q = 26 %

  A = 1 - Q = 73 % (the limit Availability – Mean Availability)

5. SNS Systems - Reliability Analysis Results

❑ **Analysis Case – Results**

Q = 2.60E-01 = 0.26; Q = 26 %

A = 1 - Q = 73 % (the limit Availability – Mean Availability)

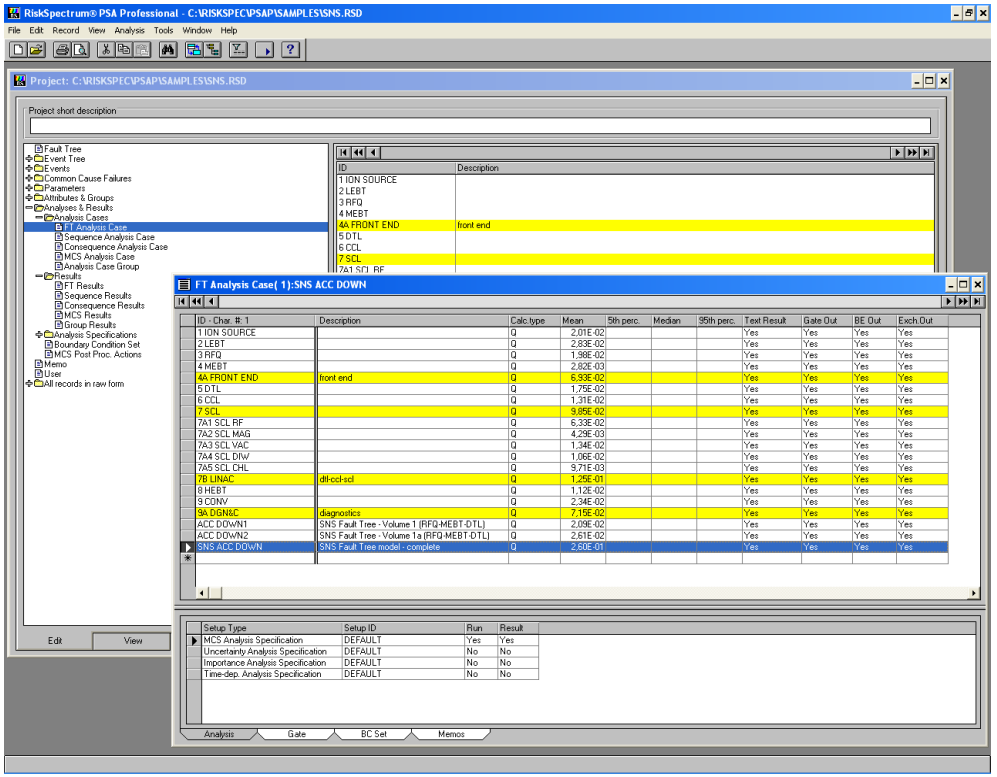
❑ **MCS Analysis** has been performed for the SNS Linac complete model **(SNS ACC DOWN)**, or **different parts (SCL, etc.)** of the accelerator, with the following **conclusions:**

➢ Results - **wide range of failure** modes for comps/systems (wide failures dispersion)

➢The **Linac, (DTL-CCL-SCL)** represents the most concerned part (Q=1.25E-01; **A=87.5%**)

➢The higher values of Unavailability:

- SCL (Q=9.85E-02; A=90%)
- DGN&C (Q=7.15E-02; A=93%)
- Front-End (Q=6.93E-02; A=93%)



➢ The most affected part of the **SCL** is the SCL RF system: Q=6.33E-02; A=94% (primarily due to power supplies failures and klystron failures, but also to cooling and vacuum malfunctions)

➢ The most affected parts of the **Front-End** are the LEBT (Q=2.83E-02; A=97%) and MEBT (Q= 2.82E-02; A=97%), more specifically the magnets the vacuum systems

5. SNS Reliability modeling – Model evaluation

❑ SNS Reliability considerations (from past operation experience)

Accelerator reliability Workshop in Cape Town, South Africa in April 2011 (G.Dodson talk)

- The **reliability of input data mix** used (RAMI static model, BlockSim model) - sources - data from staff Engineers, manufacturers (e.g. Titan, Varian, Maxwel), design reviews, etc.
- A **reliability program** has been implemented at SNS, reaching significant increase of the reliability of SNS installations in the past few years.

SNS Goals

Year	Neutron Production Availability		Integrated Beam Power (MW-hrs)	
	Commitment	Actual	Commitment	Actual
FY2007	68.0%	65.7%	117	159
FY2008	74.0%	72.0%	877	945
FY2009	80.0%	80.7%	2031	2166
FY2010	85.0%	85.6%	N/A	
FY2011	88.0%	91%YTD	N/A	
FY2012	90.0%	TBD	N/A	

❑ SNS RS Model Limitations

- SNS reliability data (MTTF; MTTR) - SNS data mix
- The reliability improvement program - not quantified/represented in the RS model.
- The LEBT and DGN&C modules - relatively developed (lack of detailed information)

➢ ***The availability results obtained by MCS analysis run separately for the different SNS Linac parts (IS, RFQ, MEBT, DTL, CCL, SCL, HEBT) have matched up very well with the SNS Logbook Availability records, although the global result is A=73%. This is attributable to the fact that the MTTF and MTTR values used for model quantification may be too conservative and other constraints above.***

➢ Considering the reliability database used for quantifying, and the fact that the last years reliability improvements have not been included in the model, ***it can be affirmed that the overall availability of the SNS Linac (A=73%) resulting from RS model is confirmed by the availability figures of the SNS from the first years of SNS operation***

5. SNS Logbook Data – Accelerator trip failures

APPENDIX 4: SNS Logbook Data – Accelerator trips failures; Availability

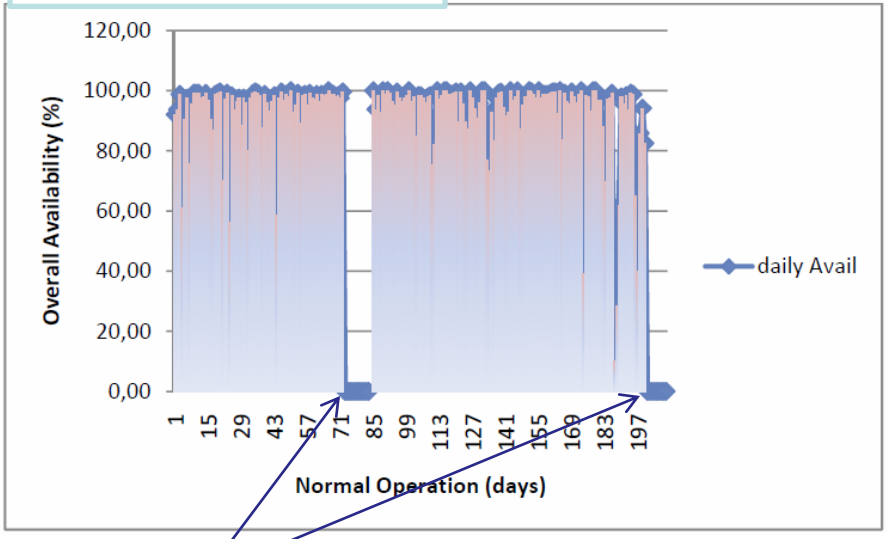
Acc. Downtime

Category	SubCategory	Hours Down(h)	Notes	Date (Shift)
Controls	Accelerator	0,2	MEBT QH03 faulting MPS	11/10/2011
Controls	Accelerator	2,6	MPS Ring Link Fault	11/10/2011
Controls	Facilities	0,6	KL-2 heat exchanger valve failure	08/11/2011
Cooling Systems	Accelerator Cooling	0,4	Momentum dump blower trips MPS	09/02/2012
Cooling Systems	RFQ Chiller	0,6	Loss of Resonance Control of the RFQ - No Clear Reason Why	14/04/2012
Cooling Systems	RCCS	0,6	DTL4 LLRF Trip - Failed Flow Meter for RF Window: FT407	02/06/2012
Cooling Systems	TRCC	1,3	Leaking water coupling on SCL20a	19/04/2012
Cryogenics System	2.1K Cold Box	0,5	CHL 2K cold box recovery	15/11/2011
Cryogenics System	2.1K Cold Box	6	Recovery of CHL from 2K coldbox trip	15/11/2011
Cryogenics System	Linac Distribution System	0,1	SCL 03b coupler temp trip; JT valve adjusted	18/12/2011
Cryogenics System	Linac Distribution System	0,3	SCL 03b coupler temp trips x3; JT adjustments	17/12/2011
Cryomodule and Superconducting RF	Cryomodule 13	0,1	SCL 13c HOM B Chatter Fault	20/06/2012
Cryomodule and Superconducting RF	Cryomodule 13	0,6	SCL 13c HOM B Chatter Fault Again	20/06/2012
Electrical Systems	AC Power Distribution	0,2	Power Dip	09/03/2012
Electrical Systems	AC Power Distribution	2,8	Starter failure for HEBT DI pump A	12/11/2011
Electrical Systems	AC Power Distribution	4,8	HEBT DI Water Pump A & B Soft Starter Failure	06/11/2011
Electrical Systems	TVA 161 KV Power	0,3	DTL Mod 5 and DH Main Trip Due to Power Dip	02/03/2012
Electrical Systems	TVA 161 KV Power	0,5	Multiple cavities and DH main trip due to lightning	22/02/2012
Electrical Systems	TVA 161 KV Power	0,5	DTL Modulators 3 & 5 SCR AC Line I faults	15/10/2011
Ion Source	Ion Source Antenna	0,1	Ion source cesiation	11/10/2011
Ion Source	Ion Source Antenna	0,5	Ion source cesiation	10/10/2011
Ion Source	Ion Source Antenna	2	Ion source recovery and tune up after source replacement	09/10/2011
Mechanical Systems	Stripper Foil Actuator	0,2	Beam off to move foil	15/03/2012
Mechanical Systems	Stripper Foil	0,3	Beam Loss Near Ring Injection Possible Caused by Foil Deterioration	18/04/2012
Mechanical Systems	Stripper Foil	0,4	Beam not transporting to target due to missing foil	12/04/2012
Mechanical Systems	Stripper Foil	6,2	Violent Foil Shaking	26/10/2011
Neutron Instruments	Beamline 14B - HYSPEC	0,3	Beamline 4b Secondary Shutter Issue Tripped IPPS	04/12/2011
Operations	Operators	0,2	Forgot to change PLC limits for HEBT DH11	04/06/2012
Operations	Operators	0,5	LEBT Chopper not Gated	04/06/2012
Operations	Operators	0,1	DTL2 LLRF Trip due to inadvertently pushing a button on the LLRF screen that turned off RF.	01/12/2011
Protection Systems	Accelerator-Personnel Protection System - PPS	0,9	Combination of three chipmunk 100 failures and 1 changeout	11/02/2012
Protection Systems	Instrument PPS	0,5	IPPS BL17 trip due to failed B power supply	30/05/2012
Protection Systems	Instrument PPS	0,5	IPPS System Trip Associated with BeamLine 17	30/05/2012
Protection Systems	Radiation Monitors	0,1	Ring chipmunk 306 fault	26/05/2012
RF Systems	HPRF	0,1	SCL 19d MPS trips	20/06/2012

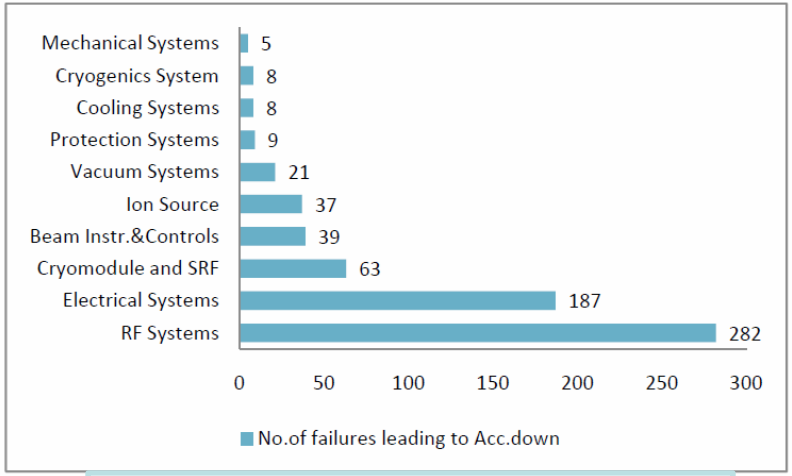
5. SNS Logbook Data – Accelerator trip failures

SNS Reliability graphics (Logbook Availability and failure data)

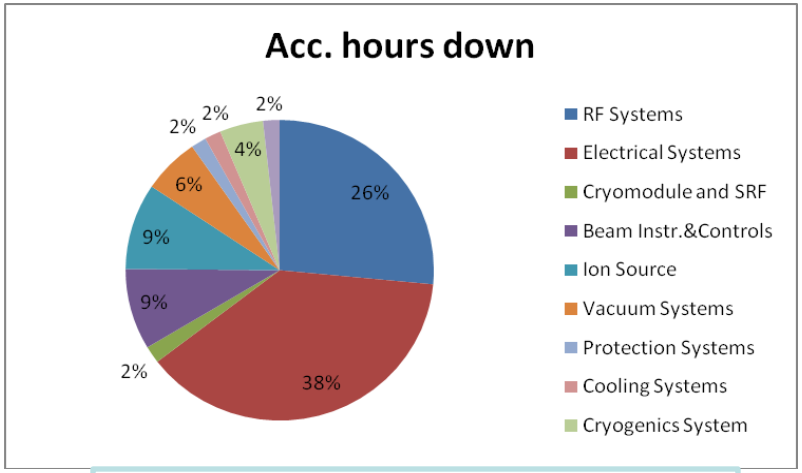
Availability (Oct.2011 - June 2012)



SNS Outages (Jan-Feb, June 2012)



Accelerator trip failures frequency (by system)

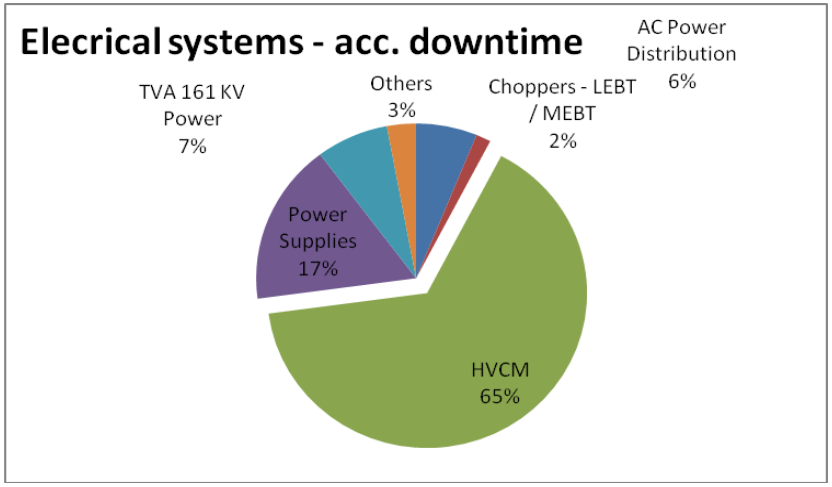


Accelerator downtime contribution (by system)

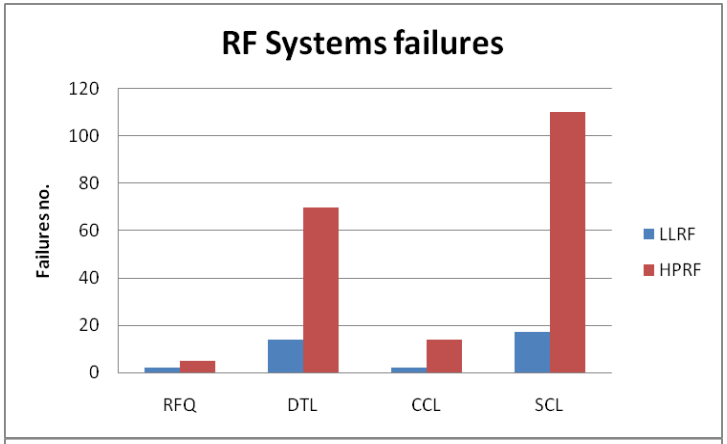
- ***RF system and electrical system failures - the most frequent;***
- ***Electrical systems failures - the most important contribution to total accelerator downtime***

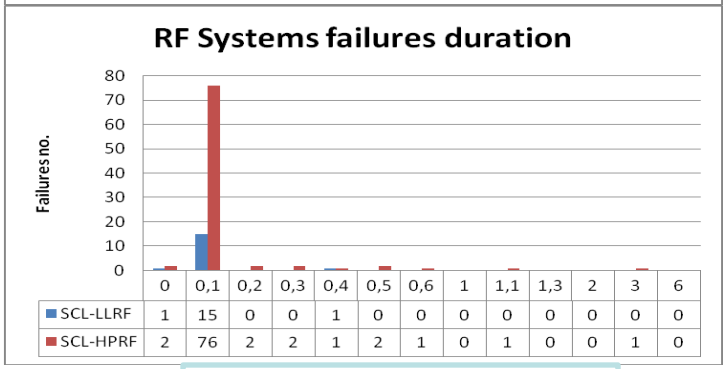
(in consonance with the conclusions from the SNS RS Model runs)

5. SNS Logbook Data – Accelerator trip failures



Electrical subsystems contribution to the acc. downtime





	0	0,1	0,2	0,3	0,4	0,5	0,6	1	1,1	1,3	2	3	6
SCL-LLRF	1	15	0	0	1	0	0	0	0	0	0	0	0
SCL-HPRF	2	76	2	2	1	2	1	0	1	0	0	1	0

RF System failures (no. & duration-hours)

The most affected subsystems of the SNS Linac (failures leading to accelerator trips):

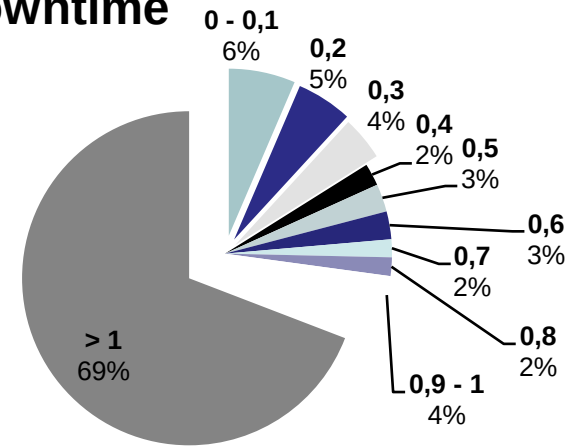
- ***SCL-HPRF (Superconducting Linac - High Power Radiofrequency)-*** *(short failures frequency)*
- ***HVCM (High Voltage Converter Modulator (****duration of trips)*

(in accordance with the SCL RS analysis)

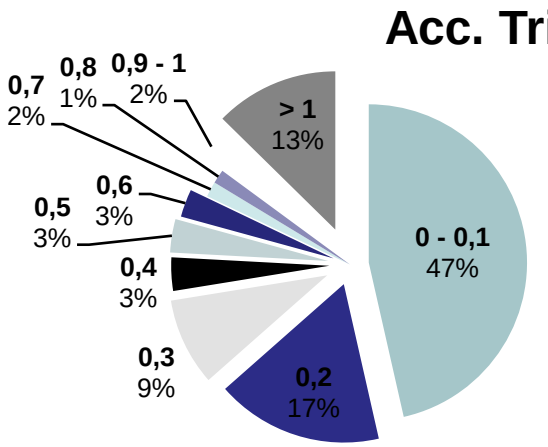
5. SNS Logbook Data – Accelerator trip failures

Statistics of accelerator trips by duration (hour fractions): failure frequency and contribution to the total downtime

Acc. Downtime



Acc. Trip failures



General context - all Linac systems: total of 705 failures recorded over the studied period of time

- ***beam interruptions of between 0 and six minutes (0 - 0.1 hours) - approx. 47 % of beam trips, i.e., 327 failures***
- ***failures whose duration exceed 1 hour represent 13 % of the total. These are the most contributing to the total downtime for the same period, which means 308 hours representing 70 % of the total (445 hours).***

6. Conclusions

- The reliability results show that the most affected SNS Linac parts/systems are:
  - SCL, Front-End systems (IS, LEBT, MEBT), Diagnostics & Controls
  - RF systems (especially the SCL RF system)
  - Power Supplies and PS Controllers

  These results are in line with the records in the SNS Logbook

- The reliability issue that most needs to be enforced in the linac design is the redundancy of the systems, subsystems and components most affected by failures

- There is a need for intelligent fail-over redundancy implementation in controllers, for compensation purposes

- Enough diagnostics have to be implemented to allow reliable functioning of the redundant solutions and to ensure the compensation function.

7. Next Steps (MAX Task 4.4)

- Development of the MAX Linac Reliability model, starting from the SNS RS Model and in consideration of the reliability analysis results and conclusions

- Iterative process – the MAX Model should be developed and continuously updated during design work, assimilating the current design information and providing recommendations for reliability improvements.

6. MAX Model – Methodology & Input Data

Overall approach

Fault Tree (based on SNS model) - Max design available info

Undeveloped Events/Systems: Reliability targets <= (Del. 1.1 – gen. machine spec.)

Fault Tree update (Del. 1.2 /design activities - WP2, WP3, Task 4.5-RF)

Reliability model: Availability / Failure (MAX shutdown) frequency

Reliability Analysis: Optimization

Design & reliability data base

Data Source: SNS, Max team, suppliers, conservative assumptions / reliability targets

Basis: SNS Model base (SNS–MAX design comp.+ **Max design specific)**

Basic Events: Component / Function Failures

Further develop: Parts/Systems of special interest; ¨critical¨ reliability issues

Support systems – gen. level

Thank you