Why Energy Extraction in the LHC ?

- **For the LHC 13 kA circuits of arc dipole and quadrupole chains:**
  - **In case of a magnet quench a rapid current decay is required after transfer of the current to the cold diode in order to preserve the diode and its associated busbars.**
  - **The alternative is a ‘Slow Power Abort’ (power restored to the Mains Network), which takes 20 min (-10 A/s) and is only possible for the dipole circuits (inversion possible as thyristor power converter, made for it). However too long in case of a quench, due to heating of diode and its associate busbars. The sa,me is true in case of no water circulation in power cables and FW path in the converter.**
- **The rapid current decay is obtained by switching external resistance into the circuit. Almost the complete stored energy shall be absorbed by the external dump resistors (99.5 % in the LHC dipole chains and 92 % in the LHC quadrupole chains).**
- **The EE systems of a main magnet chains are being activated in case of a quench, an FPA, a UPS failure or an internal problem in the EE facility itself.**

Why Energy Extraction in the LHC (contd.)?

- **For the LHC 600 A corrector magnet circuits:**
  - **No quench heaters nor by-pass diodes are installed for the corrector magnets, even when several of these are series-connected in a chain.**
  - ***Apart from the presence of parallel resistors across certain corrector magnets, protection relies on the operation of an energy extraction system***
    - **Particularly important: Short reaction time and low value of the time constant for the current decay is required due to small thermal margins for the superconducting busbars.**
  - **Two different energy extraction systems are foreseen:**
    - **Medium-voltage, separate extraction facilities**
    - **Low-voltage, converter-integrated systems**

Stored Energy in the various LHC circuits

- **Maximum values, corresponding to 13000 A and 600 A respectively:**
  - **In one Arc Dipole Chain (one Sector, 154 dipoles in series): 1318 MJ**
    - **Equivalent to the kinetic energy of a fully loaded airbus at 800 km/h or a TGV at 300 km/h.**
  - **In one Chain of Main Quads (one Sector, 51 quadrupoles in series): 20 MJ**
  - **in a 600A Corrector Circuit: 1.8 kJ - 22 kJ**
    - **Equivalent to the kinetic energy of a standard car at the speed of 60 km/h.**

- **It is not foreseen to recover the stored energy in case of extraction.**
  - **Reasons:**
    - **With the sectorisation of the LHC machine only the sector with a problem will be subjected to the extraction process. The energy to be safely recovered is, therefore, limited to the above values.**
    - **Although the energy in one dipole sector appears to be large, the cost of this energy is small (40 CHF/sector).**

When will Energy Extraction be activated in the LHC?

- Energy Extraction is a part of the <u>normal operating procedures</u> in the LHC machine
- Energy Extraction will <u>NOT</u> be used for the ordinary de-excitation of the magnet chains. Energy recuperation is possible in some of the circuits (e.g. in the Main Dipole circuits). Operating the converters in inversion will allow power feedback to the Mains Grid.
- Energy Extraction ***<u>will</u>*** be used in following cases:
  - In the event of a quench in a magnet coil or a superconducting busbar or a current lead, i.e. when a
  - In the event of a risk of damage to other components in the power circuit (e.g. no water flow for a certain time in the 13 kA water-cooled cables or problems in the by-pass crowbar system or failure in the extraction switches)
- Energy Extraction ***<u>may</u>*** be used in the following cases:
  - In dipole chains in the event of Mains failures which trip the power converter
  - In the dipole chains in the event of a failure in the Crowbar power converter failure

Principal requirements and parameters

- Current Decay:
  After transfer of the current to the extraction resistor the decay will follow a modified exponential.
- The shift is due to the presence of semiconductors in the circuit (FWT and Cold Diode)
- The 'modulation' of the exponential is due to the significant temperature elevation of the resistor body during the extraction. This modification will depend of the mass and choice of material for the resistor body.
- Design criteria:
  - Neither the voltage nor the current decay rate should at any time during the discharge exceed the initial value.

Choice of Circuit Topology
Series- or Parallel Inserted Systems?

- **In a SERIES system the dump resistor is bridging the extraction switches. One or more such systems are inserted in series with the load or parts of it**
- **In a PARALLEL system the dump resistor is bridging the magnet chain, the opening switches being located at the terminals of the power converter**
- **The SERIES TOPOLOGY requires:**
  - **a by-pass with adequate current rating across the power converter**
  - **two current leads for every load segment in case of multiple systems**
  - **space along the chain for insertion of the systems**
- **The SERIES TOPOLOGY allows:**
  - **a breakdown into smaller sub-systems, enabling**
    - **a significant reduction of the maximum voltage to ground**
    - **a sharing of the total dissipated energy between the sub- systems**
- **The PARALLEL TOPOLOGY requires:**
  - **particular measures for suppression of the leakage current through the dump resistor (always in circuit). Displacement of the DCCT to a position downstream of dump resistor may be sufficient in low-voltage systems with large Rdump**
  - **space for complete extraction system at converter terminals**
- **The PARALLEL TOPOLOGY allows:**
  - **to operate without by-pass across the power converter**

Series- or Parallel Inserted Systems? (contd)

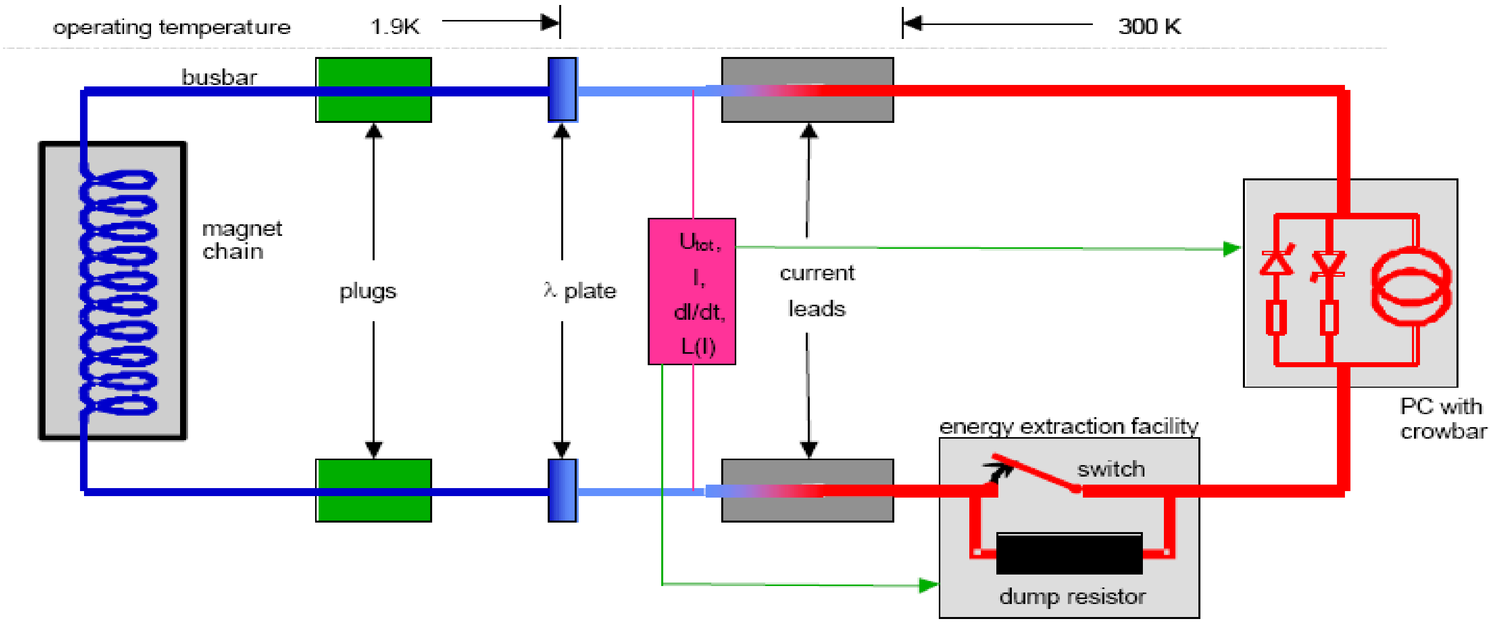
- **Further disadvantages of a PARALLEL system for LHC dipole circuits:**
  - **Although being disconnected by the switches the power converter will rise to half the peak extraction voltage (980 V) for the duration of the difference in opening times. In the double-series topology it will never rise to more than a quarter of the peak voltage.**
  - **The first opening switch will be subjected to the full peak extraction voltage until the second switch opens.**
- **A DOUBLE SERIES TOPOLOGY HAS BEEN CHOSEN FOR THE LHC DIPOLE AND QUADRUPOLE CIRCUITS**
- **The LHC dipole circuit has two symmetrically placed, 660 MJ sub-systems, one in the even point, at neg. pole of power converter and one in the odd point, at electrical circuit midpoint. With circuit earthing in the electrical midpoint of one of the two dump resistors the maximum voltage to ground can be divided by 4! (490 V instead of 1960 V). Also the voltage rating of the switches can be reduced.**

Series- or Parallel Inserted Systems? (contd)

- Also for the LHC QF/QD circuits, with only one extraction system required, a parallel topology has been favored, because:
  - By-pass diodes are anyway foreseen for the power converter
  - The low value of dump resistance would require additional blocking diodes in a parallel system

- For the 600 A Extraction Facilities, with their low ramping voltage and high dump resistance, both topologies are acceptable. However, for the external, individual extraction system, a series-topology is preferred, as
  - the converter already has a crowbar by-pass
  - mounting of the DCCT's downstream of the extraction system causes practical problems.
- For the converter-integrated facilities, a parallel system is preferable.

Energy Extraction



The Principal Energy Extraction Switches

- The extraction switch system shall be able to carry permanently the full system current. It shall be capable of reliably interrupting currents in the complete current range for transfer to the extraction resistor. ***If several switches are used in parallel for current sharing, each individual switch shall have the capability to interrupt the complete system current.***

- Two different types of switches can be used for energy extraction:

  - Semiconductor based (Thyristor or GTO -with anti-parallel diodes)
  - Electro-mechanical DC circuit breakers

- CERN has almost 10 years of experience with both types of switches and combinations for the purpose of energy extraction (LHC test benches).
- SELECTION CRITERIA: Reliability, long life-time, low losses, radiation hardness.

Selection Criteria for the 13 kA Energy Extraction switch-gear

- **ADVANTAGES / SHORTCOMINGS of the two types:**
  - **Electro-mechanical breakers can be equipped with two totally independent release systems, <u>one passive</u> (de-energizing of a 'holding' coil) and <u>one active (</u>pulsed release), whereas the semiconductor devices entirely rely on a *<u>single, active system</u>* to turn off (forced commutation by reverse cathode voltage application or gate current injection)**
  - **The voltage drop across a mechanical breaker is typically 60 mV at 4kA, against 1.4 V for a conducting power Thyristor or GTO.
A complete array of mechanical breakers for 13 kA would have power losses <u>eight times lower</u> than an equivalent Thyristor switch array (5 kW against 38 kW). For the LHC the difference would be 1.3 MW !!**
  - **A DC breaker is significantly more radiation tolerant than the semiconductor device.**
  - **The semiconductor switch needs water-cooling, the mechanical breaker is natural-air cooled.**
  - **DC breakers are by nature a protection device, built to protect highly valuable equipment against short-circuits and are, therefore, utmost reliable components.**

The LHC 13 kA Extraction Switch System
Particular CERN requirements

- **LHC application as Energy Extraction Switch requires:**
  - **Very high reliability**
  - **No mechanical Catch and Latch system. The ‘on-state’ shall be maintained only by excitation of the ‘Holding Coil’**
  - **Two completely independent release systems**
  - **The required high number of cycles shall be taken into account in the design and construction of the breaker $\mapsto$ designed for separation of the main contacts without arc, use of easily replaceable arcing contacts**
  - **Magnetic displacement of the arc for fast and reproducible arc extinction (magnetic wind)**
  - **High overload and breaking capability**
  - **Low voltage drop and losses**
  - **Protection by overload detector**
  - **Design based on industrial components, which have been in current production for at least 10 years**
- **No existing breaker on the marked satisfies all these demands !!**

VAB49

- A development was undertaken (1998) with the DC Circuit Breaker Department of Russian company “Uralelektrotyazhmash’, Ekaterinburg
- The design comprised components from 3 existing DC breakers presently protecting sub-stations, locomotives and steel works in all former USSR Republics, China and India
- The design is based on a unique, 3-limb magnetic circuit, common for the four functions: closing, holding, slow- and fast release
- The slow release is based on removal of the ‘holding’ current, the fast release is based on application of a capacitor discharge pulse
- The design features re-designed Arc Shutes and Mufflers. Two versions were made: A 1500 V model for the LHC Arc Dipole circuits and a 200 V version for the Main Quadrupoles.
- The result is a fast breaker, with typical total opening times (I.e. to full arc extinction at rated voltage and no parallel resistor) of 5 ms +-1 ms for the pulsed release and 20 ms +-2 ms for the under-voltage release.

Modeling and Computer Simulation of the Breaker Behavior for Determination of Principles and Ratings of the Control Electronics Modules

- **Optimization of the controls parameters of the strongly non-linear electro-magnetic Driving Mechanisms of the switch was obtained by computer simulations (a BINP / CERN / 'Uralelektro' collaboration).**
- **The Simulations were based on elaboration of *electrical models* of:**
  - **the magnetic circuits, including the saturation effects (piecewise linear models)**
  - **the varying air gaps of the magnetic circuit (variable controlled resistors, model with signal amplifiers)**
  - **the mechanical systems (springs, levers, armatures). All mechanical springs operate in their linear ranges.**
  - **matching between the equivalent representations of the magnetic circuits and the coils required introduction of a further equivalent circuit, representing the stored magnetic energy (representation by current-controlled voltage sources) and a feedback loop**
  - **After determination and representation of the initial conditions of the various systems, the complete model (120 elements) was constituted.**
  - **The work is presented in the Conference Paper: "Modeling and Computer Simulation of the Pulsed Powering of Mechanical D.C. Circuit Breakers for the CERN/LHC Superconducting Magnet Energy Extraction System", ICAP2000, Heidelberg.**

Milestones related to the 13 kA switch-gear

- 280 units of 4.5 kA DC breakers and 140 over-current detectors are required for the LHC machine, half for the arc dipoles, other half for the main quadrupoles.
- Prototypes of both 1500 V and 200 V versions were successfully type tested in Russia, using the CERN prototype controls electronics.
- Off-load, mechanical reliability tests (20'000 cycles) were successfully performed at the premises of the manufacturer also using the CERN-made power electronics module.
- Prototypes of both versions were subjected to Certification tests of their commutation capabilities over the current range 200 - 13'000 A. The tests were carried out according to IEC 60947-1 at an independent High-Power Laboratory (Zkusebnictvi Institute, Prague, CZ).
- An endurance test program has been conducted, during which 4 breakers were individually subjected to 2000 cycles with breaking of 13.5 kA at 1000V.
- CERN has undertaken a mechanical lifetime program, also using 4 pre-series breakers, powered from a pre-series electronics module from ECIL, India.

Milestones (continued)

- In an attempt to evaluate failure probabilities during the various phases of operation, a global risk analysis for the complete 13 kA switch facility is presently being initiated at CERN.
- The supervision of the quality assurance scheme during production of the breakers in the Urals as well as assistance during routine testing has been entrusted the Prague High-Power Test Institute.
- The production of the series of 256 units was completed at the end of 2004.
- All the produced breakers are being tested in the complete set-ups including all the other components of an extraction facility.
- Installation of the first switch assemblies in the LHC tunnel started in May 2005.

The current-equalizing Busway

- Each set of four parallel connections of each two series-connected 4.5 kA breakers will be fed through a water-cooled power Busway.
- The principal requirements to the Busway are:
  - to provide a balanced distribution of the total circuit current (13 kA) between the four branches
  - to do the job of current distribution with a minimum of voltage drop and losses (reasonably 4 kW at 13 kA)
  - to minimize the stray field outside the bus
- These requirements lead to a ***quasi-coaxial design*** (fig)
- Both a short and a long version are needed
  - SHORT version (30 units) is symmetrical with 2 branches on each side
  - LONG version (2 units, for installation in the LHC tunnel, point 3) has all eight switches on one side only (co-existence with LHC vacuum chambers)
- Hydraulically, the Busway is a part of the water-cooled cable circuit. A specially developed, 13 kA conical connector assures electrical ($0.6\mu\Omega$) and hydraulic connection to the 2000 mm^2 power cable.
- The 32 Busways will be produced at BINP, Novosibirsk, using the in-situ 'Elsib' brazing technique. Series production was completed by end of 2004.

Current-equalizing Busways for distribution of currents into the four branches of breakers.

Breaker Powering and Controls Modules

- The modeling and simulations lead to the determination of the operational sequences, permissible ranges and safety margins of all parameters of the powering and controls circuit.
- A prototype module was developed and built at CERN. Qualified during numerous tests at CERN and abroad.
- Also the Logic Controller Interface Module for Data Acquisition was developed and built at CERN.
- A pre-series of 10 cabinets was built in Europe to satisfy urgent needs for testing the DC breakers.
- Series production of 70 cabinets were covered by a collaboration agreement with India and built by the company ECIL in Hyderabad. The first units are now being installed in the LHC tunnel.

The Dump Resistors for the LHC 13 kA Circuits

- **In spite of the large energy difference (664 MJ per diode system and 22/24 MJ per quadrupole circuit) the two extraction resistor types have much in common. The basic design criteria for both types are:**
  - **In order to maintain the peak voltage across the resistor at its lowest possible level, as defined by the resistance at room temperature, a 'zero' inductance concept shall be applied and an absorber material with low temperature coefficient shall be selected.**
  - **The resistor bodies shall be dimensioned for high temperature operation, but within safe margins for long term reliability of its materials and components. Typically, the operating temperature at the end of the energy deposit shall attain 200-350 ^{o}C.**
  - **The design shall assure a perfect short- and long term reliability.**
  - **The resistor units shall be available for energy extraction without need of any infrastructure, such as mains power and cooling water, during the extraction period.**
  - **The heat dissipation to the surrounding air shall be close to zero, due to underground installation. Connection to LHC de-mineralized cooling water circuit is therefore needed for evacuation of the heat.**
  - **A design, in which the resistor body is not immersed in water, has been favored. Direct cooling by forced air is a good choice, but requires an air-to-water heat exchange. Such a device shall be incorporated in the resistor assembly.**
  - **The unit shall have its own water reservoir with sufficient capacity to assure worst-case no-boiling conditions.**
  - **The normal cooling period shall be maximum 2 hours**

Energy Extraction Resistors (contd.)

- **Particularly for the dipole resistors:**
  - **The design shall allow their installation <u>under the LHC vacuum chambers</u> in the collider tunnel (odd points). This requirement also highlights the need for <u>radiation resistance</u> of all selected materials.**
  - **With an energy deposit of 664 MJ a single, 75 mΩ unit would be 11 m long and have a mass of 8 tons. For reasons of space allocations and handling, the resistor will be composed of three individual, parallel connected sub-units. Vertical superposition is required in the UA's for limitation of floor space.**
  - **Each sub-unit has its own, built-in combined heat exchanger/ low-pressure water reservoir. The pressure is 'broken' by creation of a separate, secondary cooling circuit, common for the three sub-resistor units.**
  - **The LHC requirements are: 48 resistor units + 5 spares, each 225 mΩ +- 3 mΩ, 221 MJ.**

Dipole Dump Resistors under tests at IHEP, Protvino.

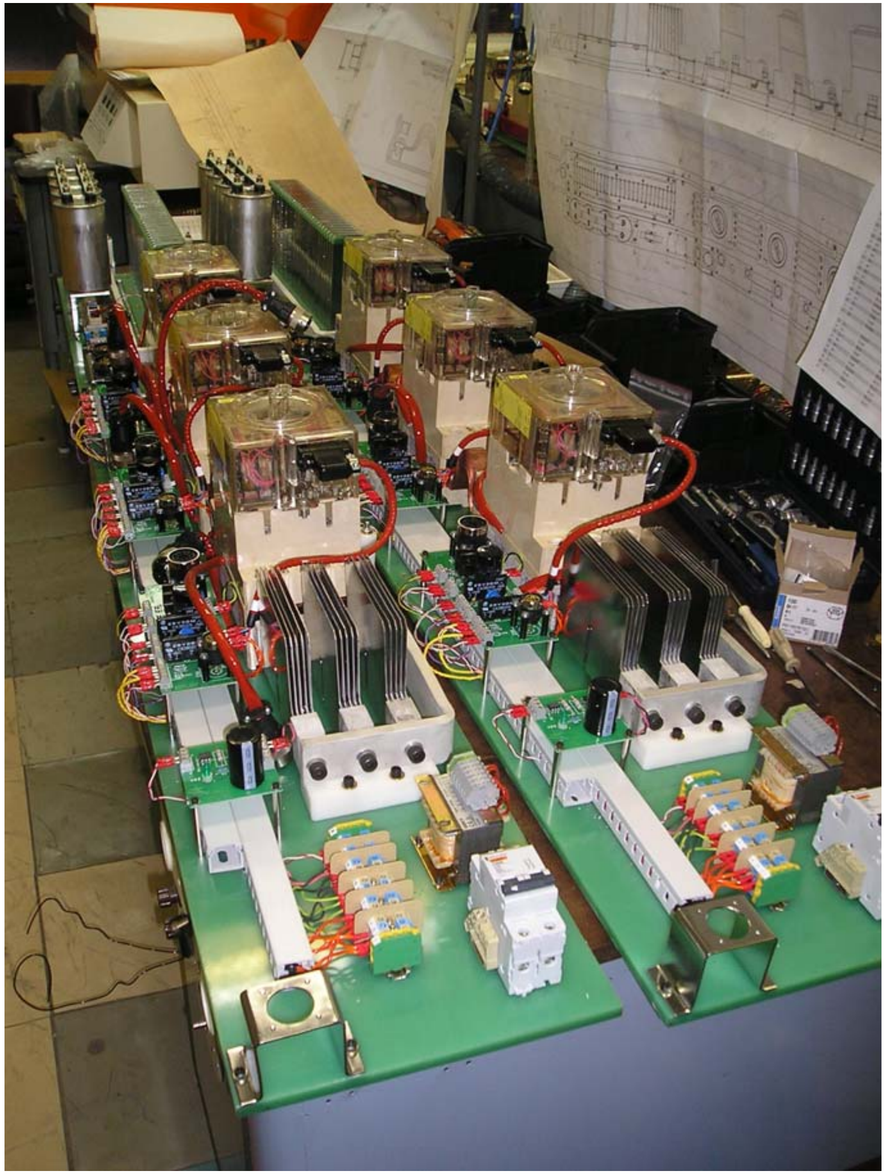
Energy Extraction Resistors (contd.)

- **Particularly for the quadrupole resistors:**
  - **The energy level of 22/24 MJ allows a rack-mounted design.**
  - **All resistor units shall be installed outside radiation areas, in the UA galleries, next to the associated 13 kA switch system.**
  - **The basic principles are the same as for the dipole resistors, except that the smaller water storage allowed the reservoir to be a high-pressure vessel with direct connection to the LHC cooling circuits.**
  - **The required quantity for the LHC is 16 + 6 spares. Half of these shall have a resistance of 6.6 mΩ (circuits with 47 series-connected quadrupoles), the other half shall have a resistance of 7.7 mΩ (51 series-connected quadrupoles). The discharge time constant is in both cases 42 s. The system voltage is low (100 V).**

600 A Energy Extraction Facilities for the LHC
History of the Project

- The project started in September 1999 with the invitation to two Russian Institutes (BINP & IHEP) to prepare preliminary proposals for a design and choice of components.
- It was finally the Institute BINP in Novosibirsk which was selected for the definitive design and production of the series of 205 systems.
- 60 systems have been supplied so far. The remaining numbers are in production.
- The first 16 systems were installed in the LHC machine late May 2005.

CERN



600 A Extraction Constructional Details

- Separate facilities, located outside the associated power converter.
- Two systems will share one standard Euro-rack.
- The chosen topology is a Series-inserted system with two main breakers, operated simultaneously.
- Short opening time is here a big issue.
- In both proposals, the extraction switch is based on Standard 3-pole electro-mechanical AC breakers, retro-fitted with DC Arc Shutes and Capacitive Snubber Circuits for arc suppression. The capacitor bank, bridging the switches, will strongly reduce the contact erosion (no additional arcing contacts), it will reduce the noise and it will shorten the arcing time. The 'military' version of these breakers are selected.
- The 600 A will be shared by the three poles in parallel.
- As it was the case for the 4.5 kA DC breaker, also these AC switches have two independent modes of release, herewith providing a four-fold redundancy.
- The system controls are made as a joint venture between the Russian Institute and CERN. The control system includes the interface to the Power Permit link and the data transmission gateway. However, the Power Abort Link is common with the associated power converter.
- All cards are made as SMD and burnt-in.

Other Basic Parameters

- **Typical total opening time with active release: 11 - 17 ms**
- **Typical total opening time with under-voltage release: 20 - 22 ms**
- **Total opening time with motor drive / electromagnetic driver: 65 ms!**
- **Maximum DC voltage across one breaker during opening: Rated value: 420 V , but successfully tested up to the double.**
- **Required Snubber Capacitance: 320 μF.**
- **Extraction Resistor: 0.7 Ω up to 1 Ω. Made from material with low temperature coefficient of resistivity, e.g. FeCrAl or SS.**
- **Equalizing resistors maybe required for current balance through the multi-pole breakers (depending on the choice of switch).**
- **All elements are natural-air cooled.**
- **Cooling time of Rdump after complete discharge with max. energy (108 kJ): Typically 20 min.**
- **Local controls and the supervision electronics mounted in a single 3U Euro-chassis.**

- **For the unlikely event of a switch-opening failure of the two main breakers, a third, identical switch is inserted in series with the two main devices and operated only in the case of a non-opening of <u>both</u> main breakers.**

Operational Aspects - related to the 13 kA Systems

- During powering of the associated magnet chain, the energy extraction facility shall ***always be operational***, ready for extraction, independent of the state of any infrastructure.
- The local powering and controls are fed from UPS. Only closing of the DC breakers rely on the Mains network.
- The DC breakers are OPENING SWITCHES, not closing switches. Repetitive closing with current may cause damage to the breaker contacts. Several precautions are taken to avoid closing with current:
  - Re-closing is inhibited as long as there's voltage across the extraction resistor(s)
  - Re-closing is inhibited as long as the temperature of the resistor body is above 50 ^{o}C.
  - Time-out of 10 min after an opening prevent re-closing during extraction.
- The facility is a part of the power enabling chain (Power Permit) as well as of the Fast Power Abort chain.
- During the closing process, all 8 switches must close and remain closed for at least 5 s. As the breaker rating allows continued operation with only 3 branches, one branch may fall out (opening by accident) without jeopardizing the operation. In the case that more than one branch is being opened all the other breakers of the system will be forced open and we have extraction.

Operational Aspects - 600 A Facilities

- **The control of the 600 A systems are generally based on the same fundamental principles as the 13 kA facilities. Only a few particularities affects the operation of these systems:**
  - **No logic is required for supervision of current branches, the 3 poles of the switches are mechanically interconnected.**
  - **There are no over-current relays**
  - **The 'Switch-Opening-Failure' Interlock will react on an identical DC breaker, located inside the extraction system itself.**

Conclusions and Final Remarks

- The 200 Energy Extraction Systems represent 296 Tons of Components
- 89 % is procured through contributions from Non-Member States (11 % from European Industry)
- All components has now been type tested and approved by CERN
- The total cost of the systems is 18 MCHF (the European Reference Price).