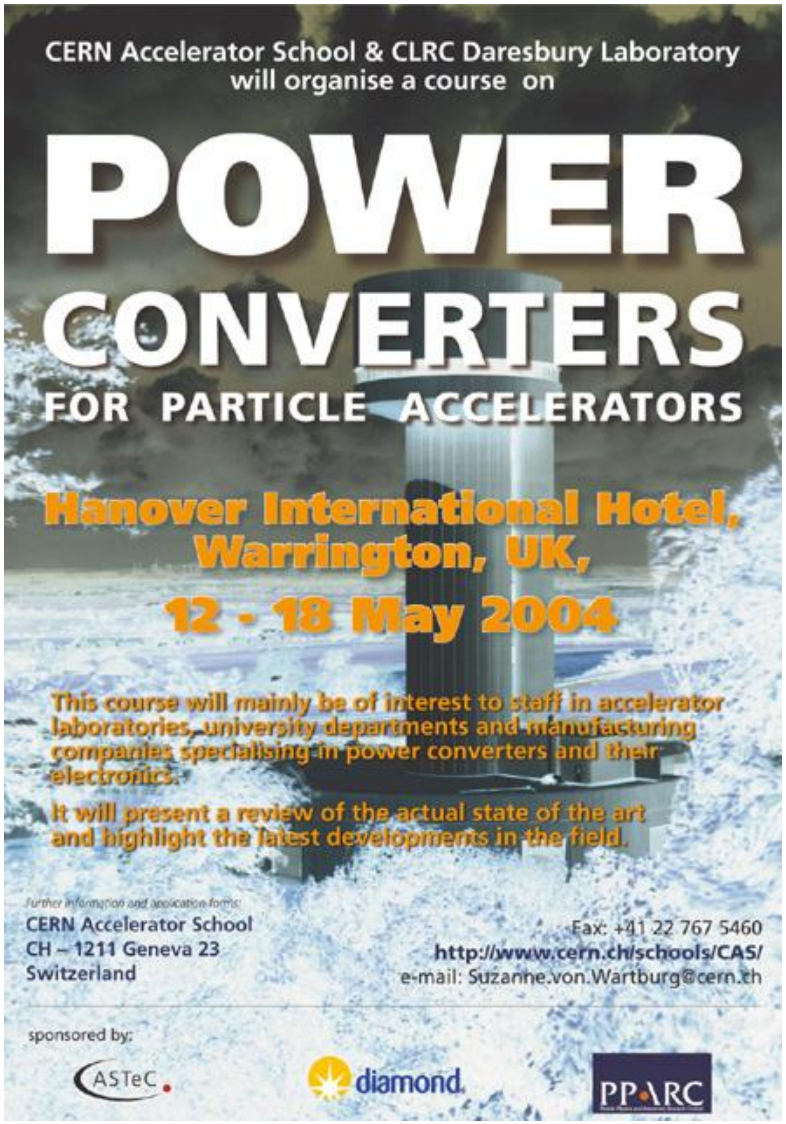
Elettra Sincrotrone Trieste

Power Converters for Accelerators

WWW (i.e. Where Were We)?



Different Power Supplies for different machines
Hans-Jörg Eckoldt

CAS
THE CERN ACCELERATOR SCHOOL

Different power supplies for different machines

Hans-Jörg Eckoldt
DESY
Warrington, UK
17.05.04

- ✓ Focused on magnet power converters
- ✓ Good overview with many examples

Where do we go now?

Eckoldt’s contribution:

✓ Detailed compendium of

- Topologies of Power Converters
- Connection of Power Converters to magnets (cycling and ramping)
- Solution adopted by several Facilities

My talk:

Performances required to power converters

vs.

Particle Accelerators’ Applications


CERN–2006–010
30 August 2006

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

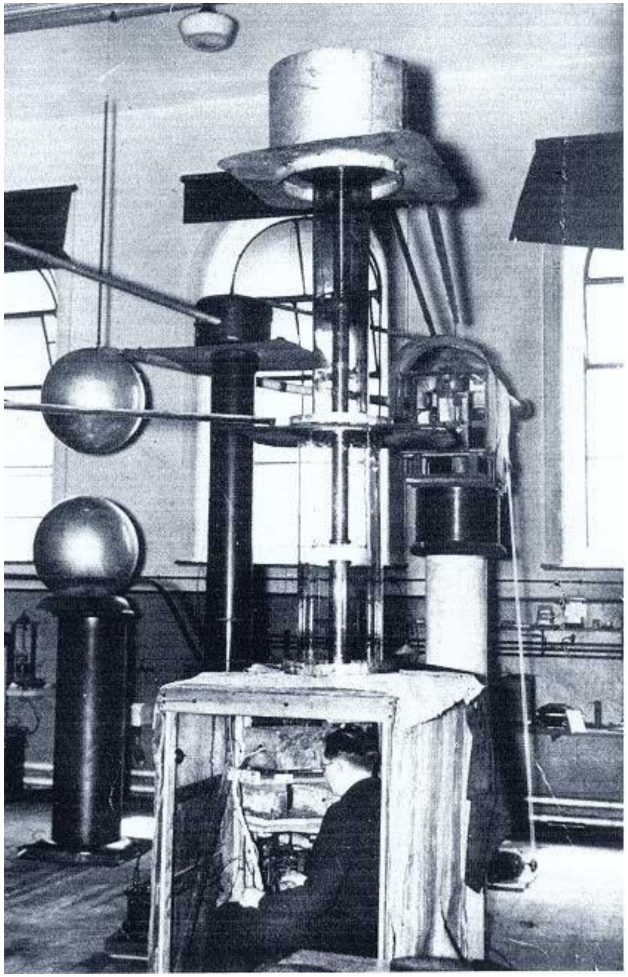
CAS CERN Accelerator School
Specialized course on power convertors

Warrington, United Kingdom
12–18 May 2004

Proceedings
Editor: D. Brandt

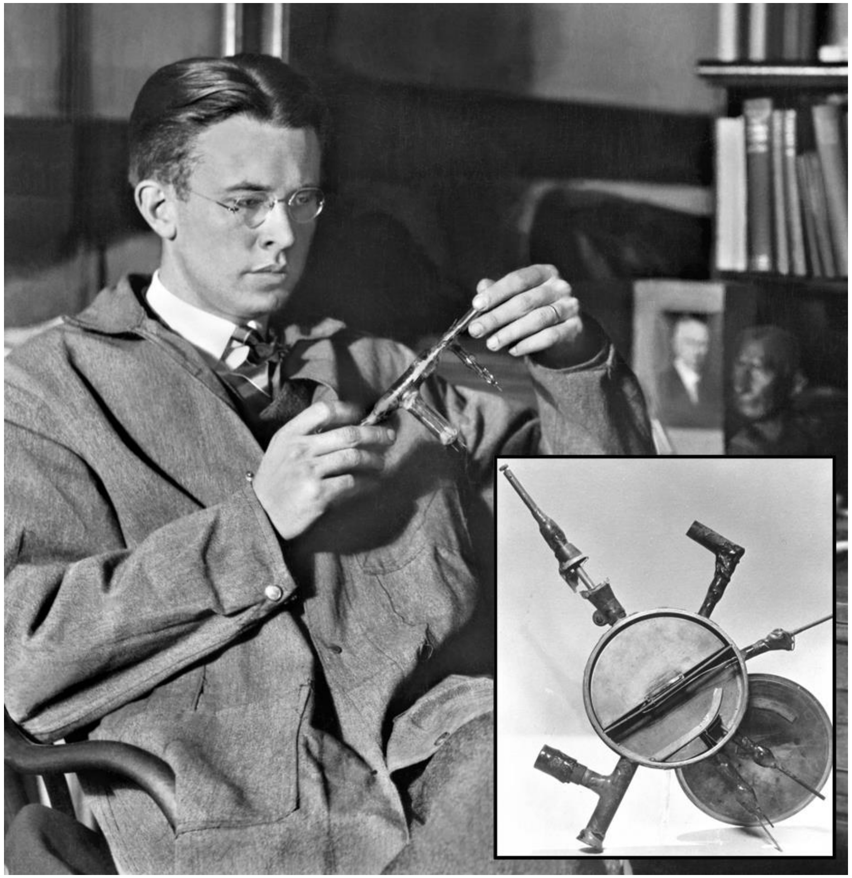
GENEVA
2006

Particle Accelerators



Cockcroft-Walton accelerator at the Cavendish Laboratory in Cambridge, England (1932).

Ernest O. Lawrence and his 4.5” (11 cm) cyclotron (1930)



(Photos collected from internet)

Classification functional to this talk

- ✓ High Energy Physics Colliders (HEP-C)
- ✓ Ion Sources/Cancer Therapy (IS/CT)
- ✓ Neutron Sources (NS)
- ✓ Light Sources (LS)

- ✓ Linear or “Open” Structures (e.g. LINACs and FELs)
- ✓ Circular or “Closed” Structures (e.g. Synchrotrons and Storage Rings)

Particle Accelerators – Common Aspects

What is it normally done?

- ✓ Production of particles
- ✓ Acceleration* of particles
- ✓ "Handling" of particles
- ✓ Measure the energy of particles

*Increase the Energy of particles

How is it done?

Specialized and dedicated equipment and subsystems

involving

Power Converters:

- AC
- DC
- Pulsed
- High Voltage
- High Current
- High Power
- …

Focus on Magnet Power Converters

- ✓ “Limit” the field
- ✓ Fascinating World (in my opinion)
- ✓ Magnets, they are ***everywhere***:
  - Magnetic lenses on the “gun” (particles source)
  - Focusing coils (e.g. on Klystrons)
  - Solenoids on accelerating structures
  - Magnets and Coils
    - *Normal Conducting*
    - *Super Conducting*
    - *DC operated*
    - *AC operated (often with “exotic” waveforms)*
    - *Pulsed*
    - *…*
  - Compensation (or correction) coils on Insertion Devices
  - …

The role of Magnet Power Converters

During and – especially – after the "Acceleration" phase:

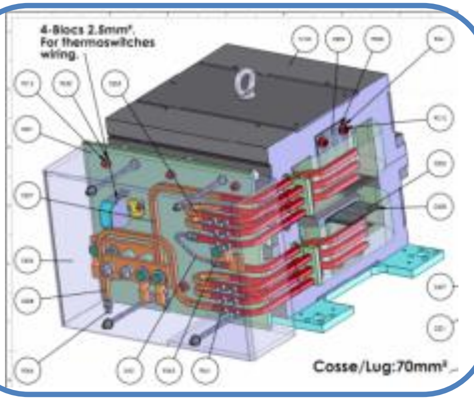
"Quality" of particle beam(s) ≡ "Quality" of the magnetic fields

"Quality" of the magnetic field (in electromagnets):

1. "Good" electromechanical design of the magnet (e.g. pole profile, coil shape, etc.)
2. "Good" excitation current ⇒ **"Good" Power Converter!**

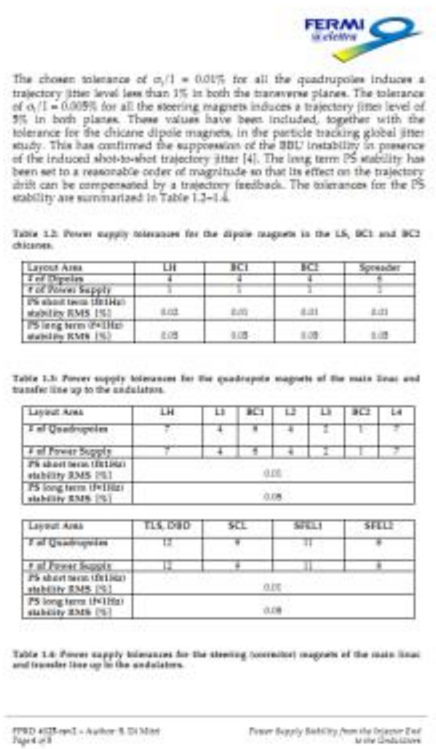
Machine Physicist’s view: a System

Elettra Sincrotrone Trieste



Magnet Design

Physics Requirements



FERMI @elettra

The chosen tolerance of σ_I/I = 0.01% for all the quadrupoles induces a trajectory jitter level less than 1% in both the transverse planes. The tolerance of σ_I/I = 0.005% for all the steering magnets induces a trajectory jitter level of 5% in both planes. These values have been included, together with the tolerance for the chicane dipole magnets, in the particle tracking global jitter study. This has confirmed the suppression of the BBU instability in presence of the induced shot-to-shot trajectory jitter [4]. The long term PS stability has been set to a reasonable order of magnitude so that its effect on the trajectory drift can be compensated by a trajectory feedback. The tolerances for the PS stability are summarized in Table 1.2–1.4.

Table 1.2: Power supply tolerances for the dipole magnets in the LS, BC1 and BC2 chicanes.

Layout Area	LH	BC1	BC2	Spreader
# of Dipoles	4	4	4	6
# of Power Supply	[illegible]	[illegible]	[illegible]	[illegible]
PS short term (f≥1Hz) stability RMS [%]	0.02	[illegible]	0.01	0.01
PS long term (f<1Hz) stability RMS [%]	[illegible]	[illegible]	[illegible]	[illegible]

Table 1.3: Power supply tolerances for the quadrupole magnets of the main linac and transfer line up to the undulators.

Layout Area	LH	L1	BC1	L2	L3	BC2	L4
# of Quadrupoles	7	4	[illegible]	4	[illegible]	[illegible]	7
# of Power Supply	7	4	[illegible]	4	[illegible]	[illegible]	7
PS short term (f≥1Hz) stability RMS [%]	[illegible]						
PS long term (f<1Hz) stability RMS [%]	[illegible]						

Layout Area	TLS, DBD	SCL	SFEL1	SFEL2
# of Quadrupoles	[illegible]	[illegible]	[illegible]	[illegible]
# of Power Supply	[illegible]	[illegible]	[illegible]	[illegible]
PS short term (f≥1Hz) stability RMS [%]	[illegible]			
PS long term (f<1Hz) stability RMS [%]	[illegible]			

Table 1.4: Power supply tolerances for the steering (corrector) magnets of the main linac and transfer line up to the undulators.

- ✓ Beam energy
- ✓ Beam size
- ✓ …
- ✓ Magnetic field and its components

Power converters

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required to the power supplies (e.g. di/dt ≥ 500 A/s, sinusoidal waveform, from to 0A to 500 A). This fact has been taken into account in defining the maximum output voltage in Table 1.

Table 1 – Power Supplies for the Dipole Magnets of the Spreader

	Value		*Unit*	*Comment*
Type of Power Supplies	Single quadrant, DC, current regulated			
Output Characteristics				
Type	A	B		A = PSB_SCL-SFEL1 B = PSB_SFEL2
# of Power Supplies	3		2 + 1 spare units	
Max. Output Voltage	25		V	Including the dynamics
Max. Output Current	500		A	
Max. Output Power	12.5		kW	
Output current Range	10 – 100		%	Or better
Current Ripple	±0. 01		%	Vs. max current (inductive load)
Current Stability	±0. 05		%	Vs. max current (≥8 hrs)
Remote current readout precision	0.1		%	Or better
Local Display Precision	0.1		%	Or better
Load Characteristics				
Load Resistance	40	24	mΩ	Magnets in series + cables
Load Inductance	14.4	7.2	mH	Magnets in series
Interfaces				
To Control System	Ethernet		TCP IP socket (see paragraph 4.3.2)	
To interlock System	Contacts		See paragraph 4.3.5	

Notes

- *Maximum Output Voltage*: the voltage required to supply the nominal load with the maximum current – including dynamics.
- *Maximum Output Current*: the maximum current required by the magnets (the safety margins have been included in the magnetic design)
- *Maximum Output Power*: the maximum DC power of the power supplies.
- *Output Current Range*: the range within which it must be possible to vary the DC level of the output current without exceeding the required performances; the range can be wider with reduced performances.

FTSD-PS #05 rev. 0.1 – Author: Roberto Visintini
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Power Supplies for the Dipole Magnets of the Spreader of FERMI

Physics, Magnetics, Power, Control: a System

Magnet Designer

Power Converter Designer

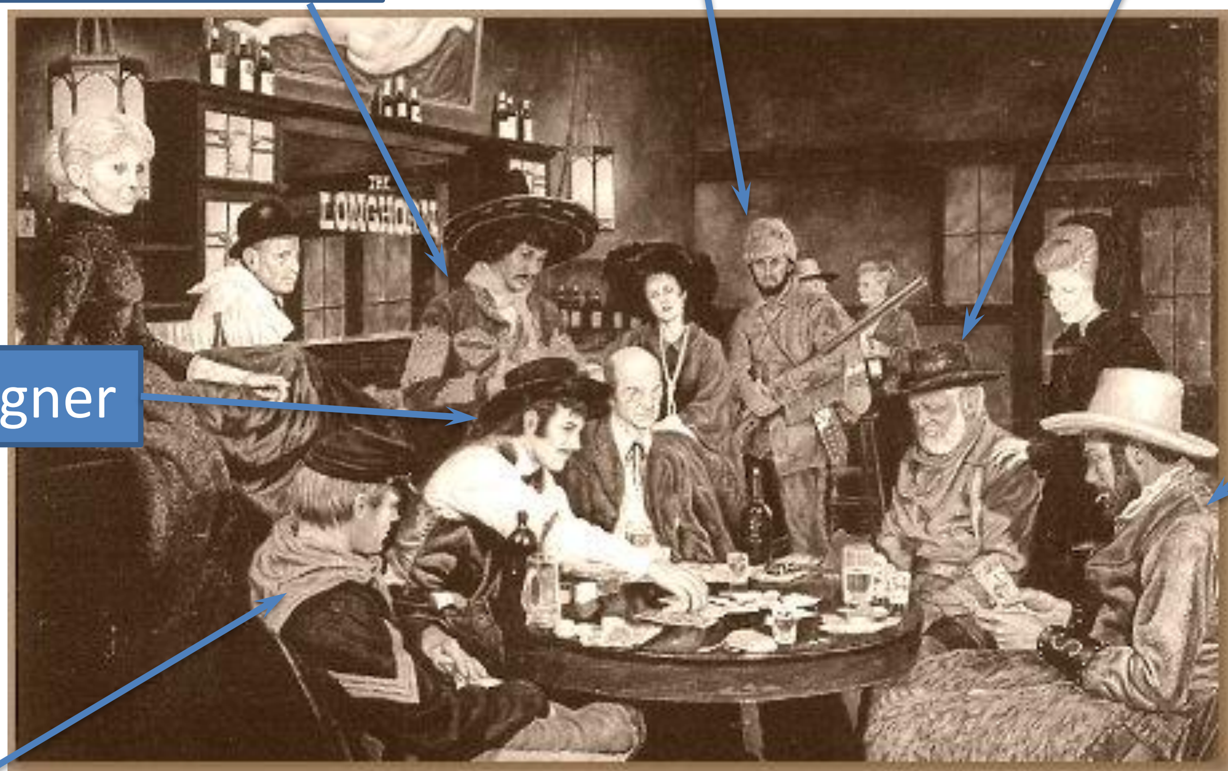
Particle Physicist

Controls Expert

Defining the Parameters of the power converters is not a Chess Tournament where players meet singularly…

Physics, Magnetics, Power, Control: a System, integrated in the plant!

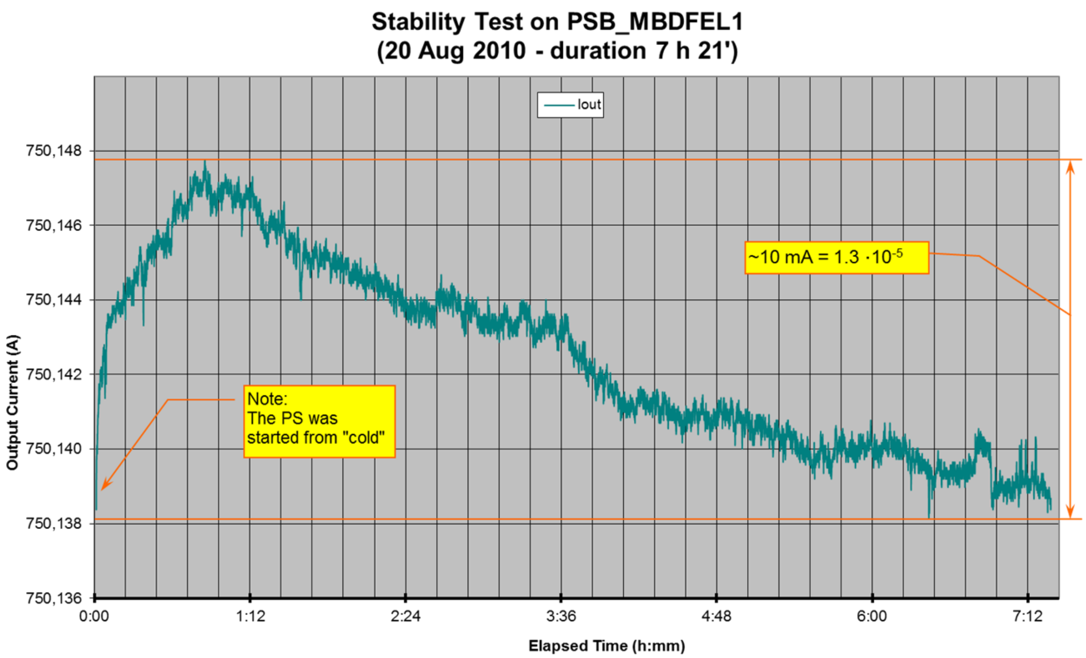
…it is more a poker game, with spectators waiting for their turn to play!



Some Definitions – 1

✓ Current Stability

Long term drift (a percentage of full-scale), over some hours at fixed line, load, and temperature, after a warm-up period.



✓ Current Ripple

Noise on the output current specified as a percentage of full scale. The frequency spectrum depends on the technology adopted and frequency of commutation of the switches.

Some Definitions – 2

- **Resolution (set and read-back)**

  The smallest possible steps for adjustment of the current set-point or the current read-back, specified as a percentage of full-scale or number of bits.

- **Reproducibility**

  Reproducibility of the actual output current, for the same current set-point (at different times) of a desired output value under constant conditions, specified as a percentage of full-scale.

- **Accuracy (set and read-back)**

  How close the actual output current is to the current set-point or to the current read-back, specified as a percentage of full-scale.

Particle Accelerators vs. Power Converters

A. Very large number of Particle Accelerators (also taking in account only those currently in operation…)

B. Large number of magnet power converters' types in each Particle Accelerator

$$\mathbf{A \times B = C \quad with\ C \rightarrow \infty}$$

(practically, NOT mathematically)

✓ HEP-C, IS, CT, NS, and LS

✓ Limited Number of Examples

I apologize for not citing YOUR Facility!

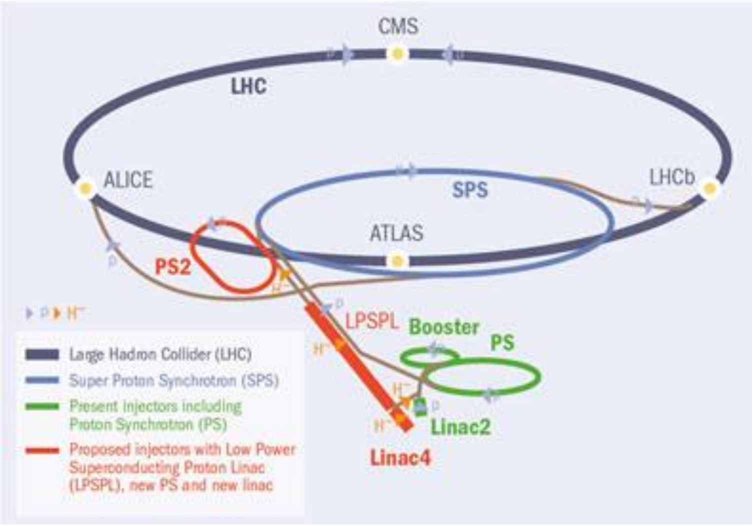
(The following images are taken from Facilities' Web Sites)

High Energy Physics Colliders (HEP-C)

- ✓ **Very High Energy of particles (TeV)**
- ✓ **Large Dimensions (counting in some km)**
- ✓ **Superconducting magnets**
- ✓ **Great number of magnet power converters**

HEP-C: LHC (CERN, CH, 2008-2009)

- ✓ **Large complex of accelerators**
- ✓ **7 TeV (3.5 TeV + 3.5 TeV) energy**
- ✓ **27 km circumference**
- ✓ **~9600 Superconducting magnets**



HEP-C: LHC (CERN, CH, 2008-2009)

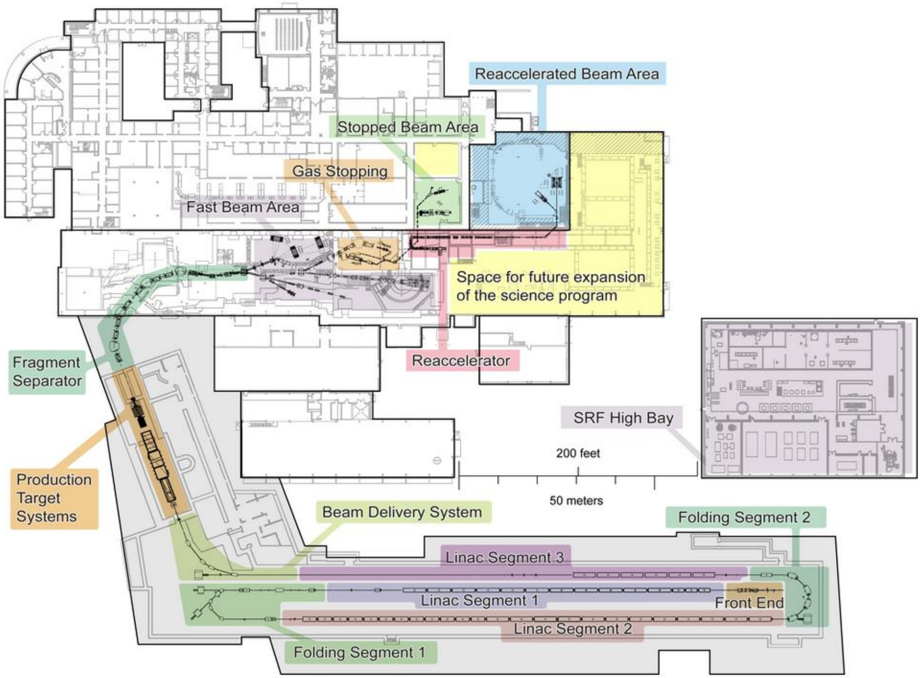
PC type	Qty	Switch Type	½ hour stability
MB [13kA/±190V]	8	SCR	3 ppm
MQ [13kA/18V]	16	SM	3 ppm
Inner Triplet [5..7kA/8V]	16	SM	5 ppm
IPD and IPQ [4..6kA/8V]	174	SM	5 ppm
600A type 1 [±0.6kA/±10V]	400	SM	10 ppm
600A type 2 [±0.6kA/±40V]	37	SM	10 ppm
120A [±120A/±10V]	290	SM	50 ppm
Orbit correctors [±60A/±8V]	752	SM	50 ppm
Warm magnets [1kA/450..950V]	16	SCR	20 ppm

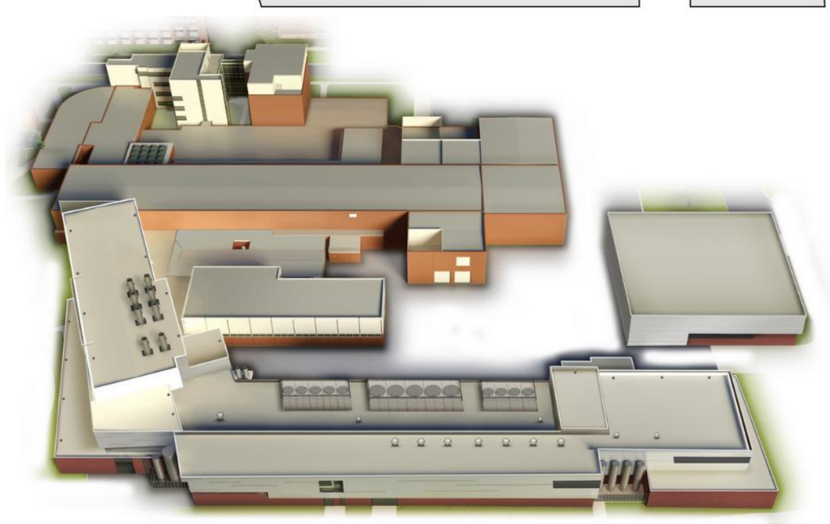
- ✓ More than 1700 PCs
- ✓ High Current (up to 13 kA)
- ✓ Thyristor (SCR) of Switch Mode (SM)
- ✓ Smaller Units in Parallel
- ✓ Custom-made PCs
- ✓ Collaboration with Industry in developing the PCs
- ✓ High reliability: almost all PCs are located underground and not easily accessible

Ion Sources (IS)

- ✓ **Low Energy of particles (hundreds of MeV)**
- ✓ **Medium Dimensions (in some hundred meters)**
- ✓ **Different Accelerators (Cyclotrons, LINACs,…)**
- ✓ **Superconducting and Normal conducting magnets**
- ✓ **Great variety and number of magnet power converters**

IS: FRIB (USA, under construction)





- ✓ Rare Isotope Beams
- ✓ Linear Accelerators (LINACs)
- ✓ Mix of Magnetic and Electrostatic elements (Dipoles and Quadrupoles)
- ✓ Mix of Normal- & Super-Conducting Magnets
- ✓ High Current and High Voltage
- ✓ 1-Q, 2-Q, 4-Q Power Converters
- ✓ Use of COTS (Commercial Off The Shelf) power converters
    - Cost
    - Availability
    - Reliability
    - Maintanance and Spares

IS: FRIB (USA, under construction)

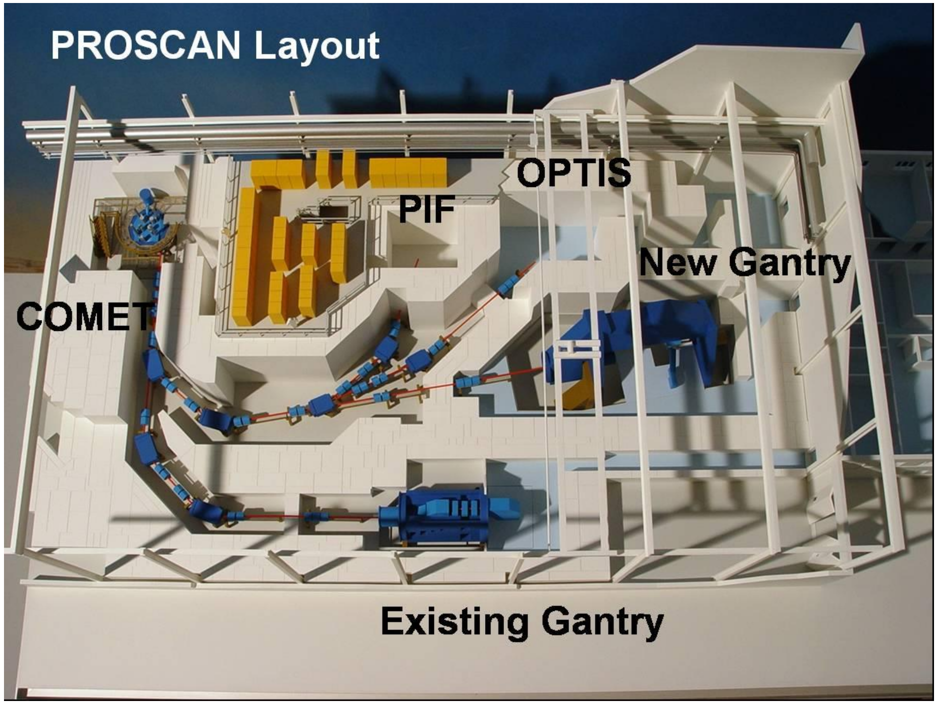
Electrostatic Devices						
Qty	Iout (mA)	Vout (kV)	Long Term (ppm)	Ripple (ppm)	Accuracy (ppm)	Resolution (ppm)
11	1 – 60	1 – 100	±100 - ±500	100 - 200	1000	500

Magnetic Devices						
Qty	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Accuracy (ppm)	Resolution (ppm)
194	2 - 3500	6 – 600	±200 - ±1000	50 - 400	2500-4000	20 – 200

Cancer Therapy (CT)

- ✓ Accelerator Facility <u>and</u> Clinical Facility
- ✓ Low Energy (hundreds of MeV)
- ✓ Small Dimensions (counting in tens of meters)
- ✓ Different Types of accelerators (Synchrotrons, Cyclotrons,…)
- ✓ Different Types of Power Converters (SCR, Switched mode, linear)
- ✓ Extremely high reliability (e.g. avoid failures during treatment)
- ✓ Minimize time for repair of systems

CT: PROSCAN (PSI, CH, 2007)



The COMET cyclotron (under construction in 2004).

- ✓ **Super Conducting Cyclotron**
- ✓ **Protons (250 MeV)**
- ✓ **Treatment beamlines for eye radiotherapy, for deep-seated tumors**

CT: PROSCAN (PSI, CH, 2007)

Type	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Reprod. (ppm)	Accuracy (ppm)	di/dt [A/s]
IGBT	500	350	100	50	100	500	125
IGBT	220	320		1000		1000	11.000
IGBT	220	285	15	15	100	500	100
IGBT	150	175		1000		1000	40.000
IGBT	150	90	100	50	100	500	100
MOSFET	50	50	500	100	500	500	
MOSFET	10	24	500	100	500	500	

- ✓ About 100 Power Converters
- ✓ All 4Q PC
- ✓ PWM (IGBT & MOSFET)
- ✓ Focus on dynamics: tight requirements on di/dt and regulation delays

CT: CNAO (Italy, 2010-2012)

- ✓ **Synchrotron based (80 m circ.)**
- ✓ **250 MeV (protons)**
- ✓ **480 MeV (carbon ions)**
- ✓ **Heavy, large deflection angle dipole (90 deg)**

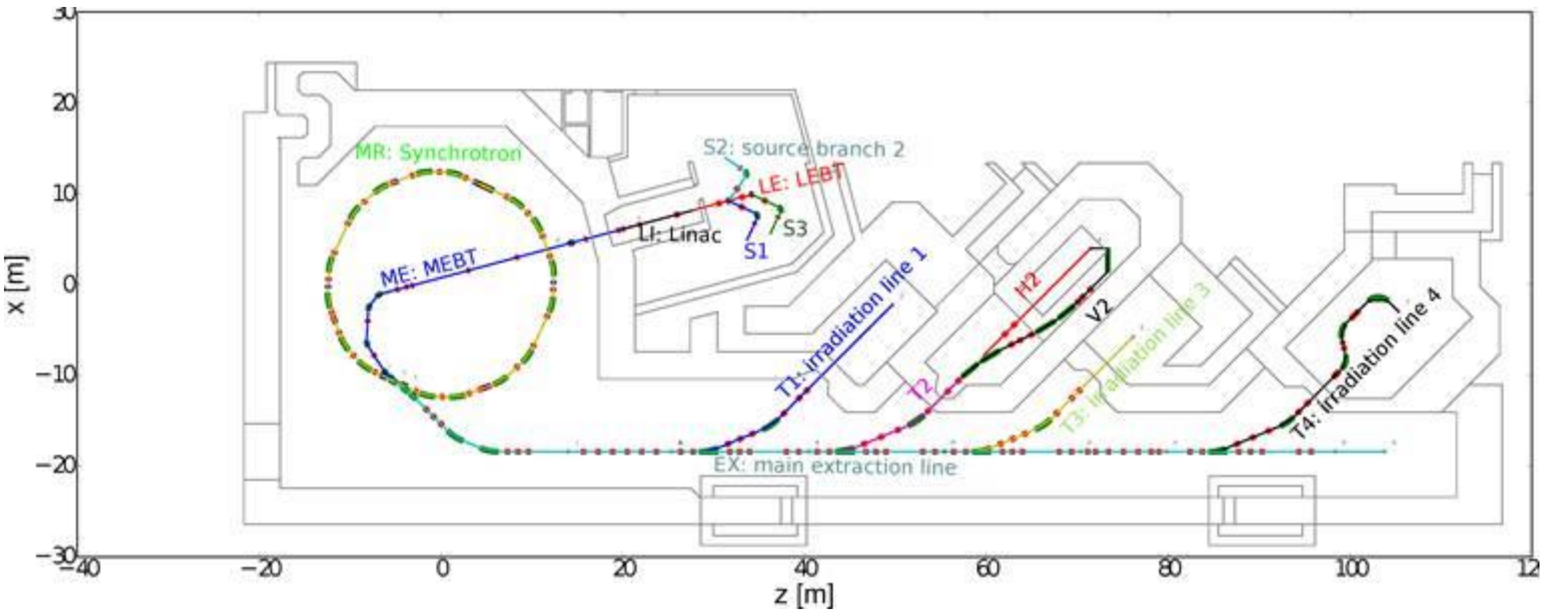
CT: CNAO (Italy, 2010-2012)

Mag	Type	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Reprod. (ppm)	Res'n (ppm)
Dip	SCR + SM-AF	3000	±1600	±5	±5	±2.5	±5
Dip	SCR + SM-AF	3000	±110	±25	±25	±13	±25
Dip	SCR + SM-AF	2500	±450	±5	±5	±2.5	±5
Dip	PWM	±550	±660	±200	±100	±100	±60
Dip	PWM	±30 - 300	±20 - ±35	±50 - ±500	±50 - ±250	±25 - ±500	±50 - ±1000
Q + Sxt	PWM	150-650	±17 - ±65	±50 - ±100	±50 - ±100	±25 - ±50	±50 - ±100
Corr	Bip. Linear	±30 - ±150	±15 - ±30	±500	±250	±500	±1000

- ✓ Over 200 Power Converters
- ✓ HV & HI at the same time (at LHC: 13 kA but “only” 200 V…)
- ✓ High reproducibility requirements
- ✓ SCR, PWM, Linear
- ✓ Active filtering on the AC side of the large SCR Bridges

CT: MedAustron (Austria, under construction)

- ✓ Synchrotron based (80 m circ.)
- ✓ Ion sources with LINAC pre-accelerator
- ✓ Protons (60 - 250 MeV)
- ✓ Protons 800 MeV (non-clinical research)
- ✓ Carbon Ions (120 – 240 MeV/n)
- ✓ Built in collaboration with CERN



CT: MedAustron (Austria, under construction)

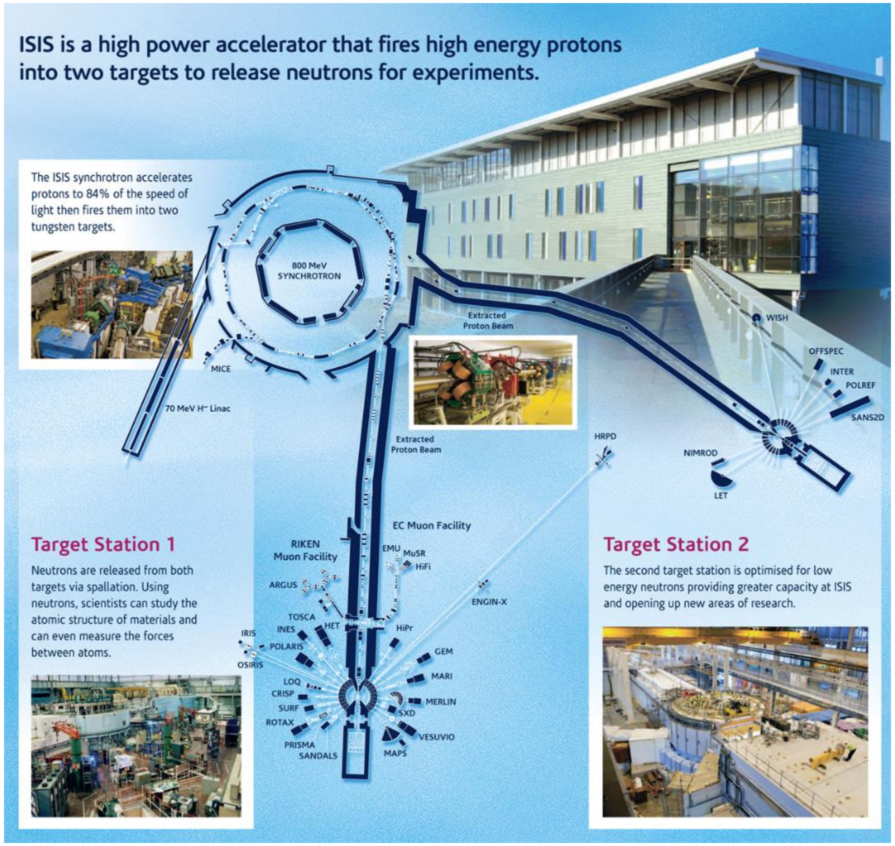
- ✓ More than 200 Power Converters
- ✓ Repetition rate 0.5 Hz
- ✓ 1.5 kW up to 4.5 MW of peak output power
- ✓ 4Q PWM
- ✓ Precision range 10 ppm – 100 ppm
- ✓ Dynamics: 100 Hz (most of PC) and 2 kHz (scanning magnets)
- ✓ PC as Voltage Sources from manufacturer and High precision digital current regulation system provided by CERN/MedAustron

Neutron Sources (NS)

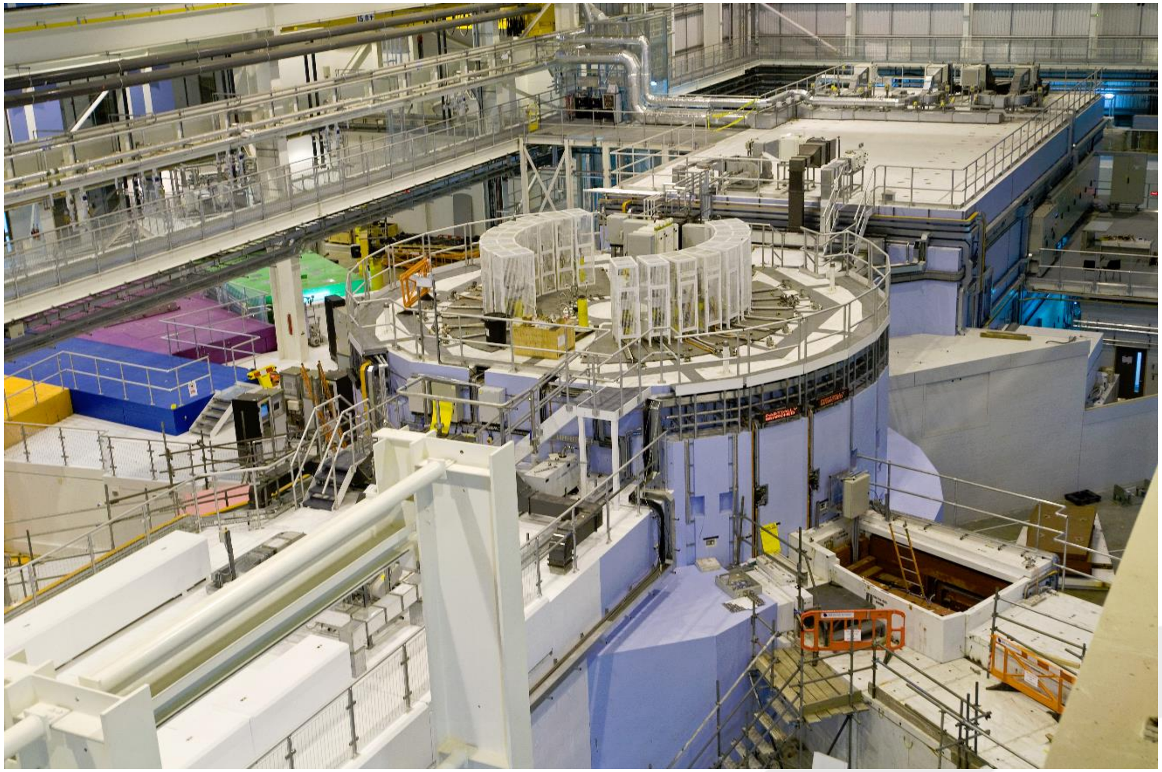
- ✓ **Mid-Low Energies (0.8 – 2.5 GeV)**
- ✓ **Medium Dimensions (up to some hundred meters)**
- ✓ **Linear or Circular accelerators**
- ✓ **Spallation principle**

From Wikipedia, file:Spallation.gif

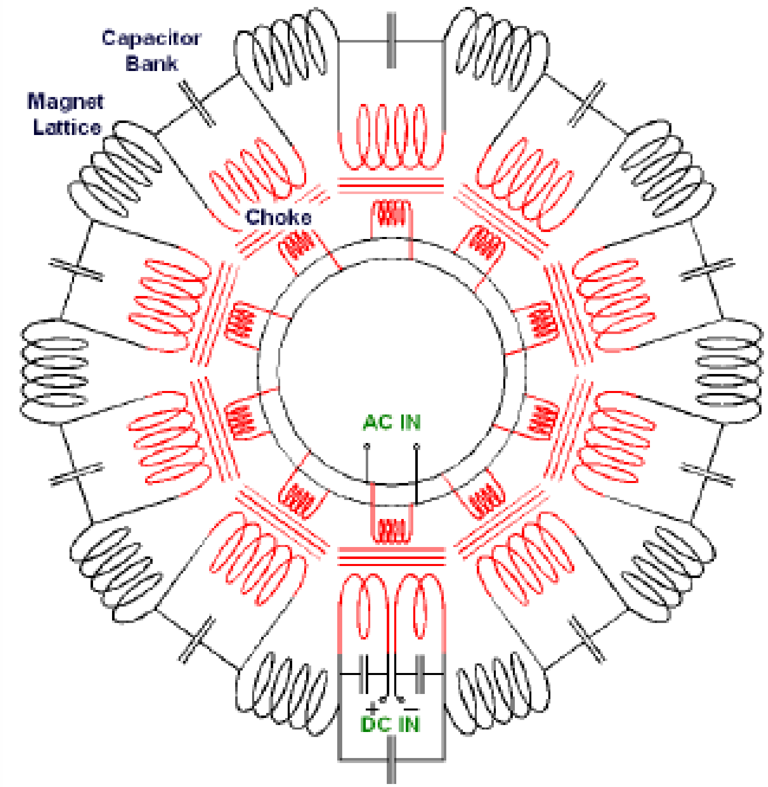
NS: ISIS (UK, 1985)



- ✓ **800 MeV proton accelerator**
- ✓ **Linac Pre-accelerator (70 MeV)**
- ✓ **Synchrotron (~165 m circumference)**
- ✓ **50 Hz cycles**



NS: ISIS (UK, 1985)



- ✓ White-Circuit arrangement (10 chokes)
- ✓ 50 Hz resonant
- ✓ 1 MJ (10 x 100 kJ) energy storage in normal conducting chokes
- ✓ DC Power converter: ~660 A DC bias
- ✓ AC Power Converter: 4x300 kVA UPS
- ✓ The rated secondary AC rms voltage is 14.4 kV at 1022 A

Light Sources (LS) – SRs and FELs

Storage Ring

- ✓ Circular
- ✓ Mid-High Energy of particles (1.5 – 8 GeV)
- ✓ Mid Dimensions (hundreds of meters up to few km)
- ✓ Normal and Superconducting magnets
- ✓ Great number of magnet power converters

FEL

- ✓ Linear
- ✓ High Energy of particles (1.5 – 20 GeV)
- ✓ Mid Dimensions (hundreds of meters up to few km)
- ✓ Normal and Superconducting magnets
- ✓ Great number of magnet power converters

Light Sources (LS) – SRs and FELs

Storage Ring

1. Elettra (Italy, 1993)
2. APS (USA, 1995)
3. LNLS (Brazil, 1997)
4. SLS (Switzerland, 2000)
5. SSRL-SPEAR3 (USA, 2003)
6. Soleil (France, 2006)
7. DLS (UK, 2006)
8. ALBA-CELLS (Spain, 2010)
9. DESY (Germany, 2010)
10. MaxIV (Sweden,…)

FEL

1. LCLS (SLAC, USA, 2009)
2. FERMI (Elettra, Italy, 2011)
3. SwissFEL (PSI, Switzerland,…)
4. XFEL (DESY, Germany,…)

LS-SR: Elettra (Italy, first beam 1993)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res’n (bit)	Type
Dip SR	2000	560	±200	±40	16	SCR
Q + Sxt SR	300	40 - 660	±200 - ±500	±20 - ±50	16	SCR
Corr SR	±16	±80	±500	±50	16	Bipolar Linear

- ✓ 2.0 and 2.4 GeV
- ✓ 264 m circumference
- ✓ About 300 Power Converters
- ✓ SCR and Bipolar Linear

LS-SR: APS (USA, first beam 1995)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (bit)
Dip SR	550	750	±30	±40	16
Q SR	500	20	±60	±800	16
Sxt SR	250	25	±300	±200	13
Corr SR	±150	±20	±30	±1000	13

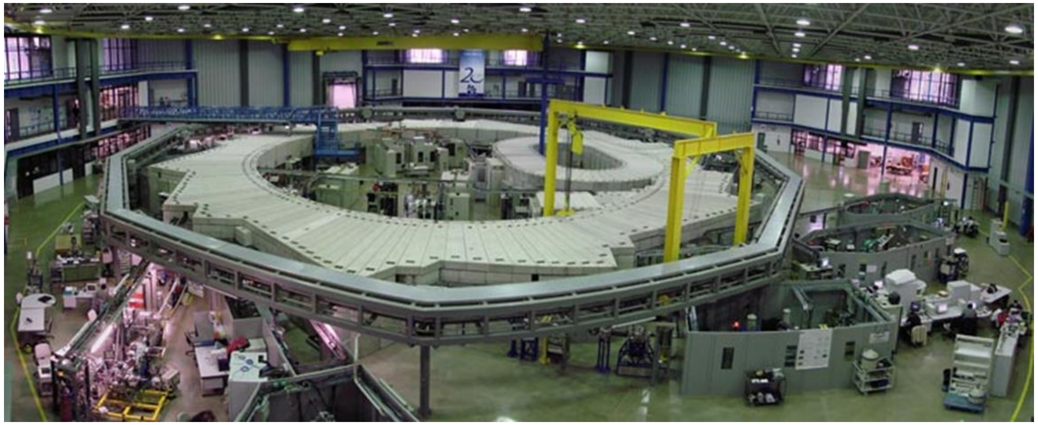
Ph.Tigerhill Studio, Argonne National Laboratory.

- ✓ 7 GeV
- ✓ 1100 m circumference
- ✓ More than 1100 Power Converters
- ✓ SCR and PWM

LS-SR: LNLS (Brazil, first beam 1997)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (bit)	Type
Dip SR	300	950	±100	±70	16	SCR
Q + Sxt SR	10 - 220	10 - 45	±1000 - ±100	±1000 - ±100	16	SCR/PWM
Corr SR	±10	±10	±1000	±100	16	Bipolar Linear

- ✓ 1.37 GeV
- ✓ 93 m circumference
- ✓ About 200 Power Converters (including Booster)



LS-SR: SLS (PSI, CH, first beam 2000)

Mag PC	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (bit)	Accuracy (ppm)
Dip SR	500	880	100	15	16	100
Q + Sext SR	70 - 140	35 - 145	100	40 - 100	16	100
Bipolar SR	±7	±24	100	15	18	1000

- ✓ 2,4 GeV
- ✓ 288 m circumference
- ✓ About 640 Power converters (Overall)

LS-SR: SSRL-SPEAR3 (USA, first beam 2003)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Type
Dip SR	800	1200	20	12p SCR Bridge +PWM
Q SR	100	100 - 700	100	12p Diode Bridge +PWM / PWM
Sext SR	225	600	100	12p Diode Bridge +PWM / PWM
Corr SR	±30	±50		PWM
Dip TL	500	45		PWM
Q TL	60	80		PWM

- ✓ 3 GeV
- ✓ 234 m circumference
- ✓ About 250 Power Converters (incl. TLs)

LS-SR: Soleil (France, first beam 2006)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Resolution (ppm)
Dip SR	580	610	10	10
Q + Sxt SR	250 - 350	14 - 140	20 - 50	5 - 50
Corr SR	±7 - ±14	±3.5 - ±14	20 - 50	2 - 30
Dip TL	250 - 580	20 - 80	50 - 100	60 - 100
Q TL	10 - 275	9 - 10	50 - 100	20 - 60
Corr TL	±1.5 - ±10	±2.5 - ±9	100 - 500	60 - 100

- ✓ 2.75 GeV
- ✓ 354 m circumference
- ✓ About 350 Power Converters (incl. TLs)
- ✓ 12p Diode Bridge +PWM (D & S), PWM (Q & C)

LS-SR: DLS (UK, first beam 2006)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (ppm)	Reprod. (ppm)	Bandw. (Hz)
Dip SR	1500	530	±10	±10	4	10	DC
Q + Sxt SR	100 - 350	17 - 41	±10	±10	4	10	DC
Corr SR	±5	±20			4	10	50

- ✓ 3 GeV
- ✓ 560 m circumference
- ✓ About 1000 Power Converters
- ✓ PWM with Digital Regulation

LS-SR: ALBA-CELLS (Spain, first beam 2010)

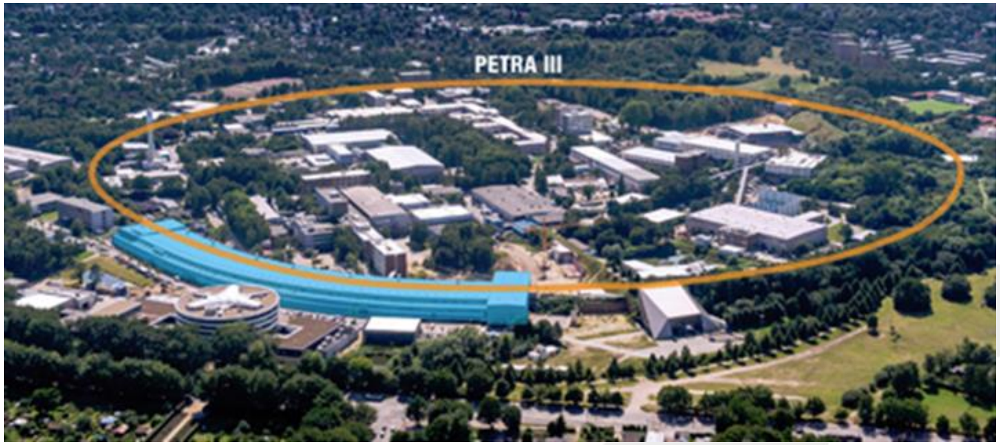
Mag	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (ppm)
Dip SR	600	750	±10	10	5
Q SR	200 - 225	15 - 25	±10	10	5
Sxt SR	215	100 - 350	±50	50	15
Corr SR	±12	±60	±20	10	5
Dip TL	12 - 180	12 - 60	±15	15	15
Q TL	15 - 170	15 - 20	±15	15	15
Corr TL	±2 - ±6	±2 - ±10	±100		100

- ✓ 3 GeV
- ✓ 267 m circumference
- ✓ Almost 400 Power Converters (including Booster-based Injector)
- ✓ PWM with digital regulation

LS-SR: PETRA III (DESY, Germany, 2010)

Note	Type	Iout (A)	Vout (V)	Ripple (Vout rms)	Accuracy (ppm)	Res'n (bit)
	TL to PETRA	200 - 400	60 - 120	2-3 V	100	16
White C.	Dipole AC	1004	1330		10	20
White C.	Dipole DC	520	1560		10	20
White C.	Quad	650	250		10	20
White C.	Sextupole	200	85		10	20
SCR	PETRA III	600	300	3	100 (30)	18
PWM	PETRA III	200 - 600	60 - 120	2-3 V	100 (10)	20
PWM Cor.	PETRA III	±5 - ±55	±40 - ±60	2-3 V	500 (10)	20

- ✓ **Electron-Positron Collider in 1980s**
- ✓ **Pre-accelerator for HERA**
- ✓ **2.3 km circumference**
- ✓ **Analog or Digital regulation**
- ✓ **Mix of technologies and topologies**



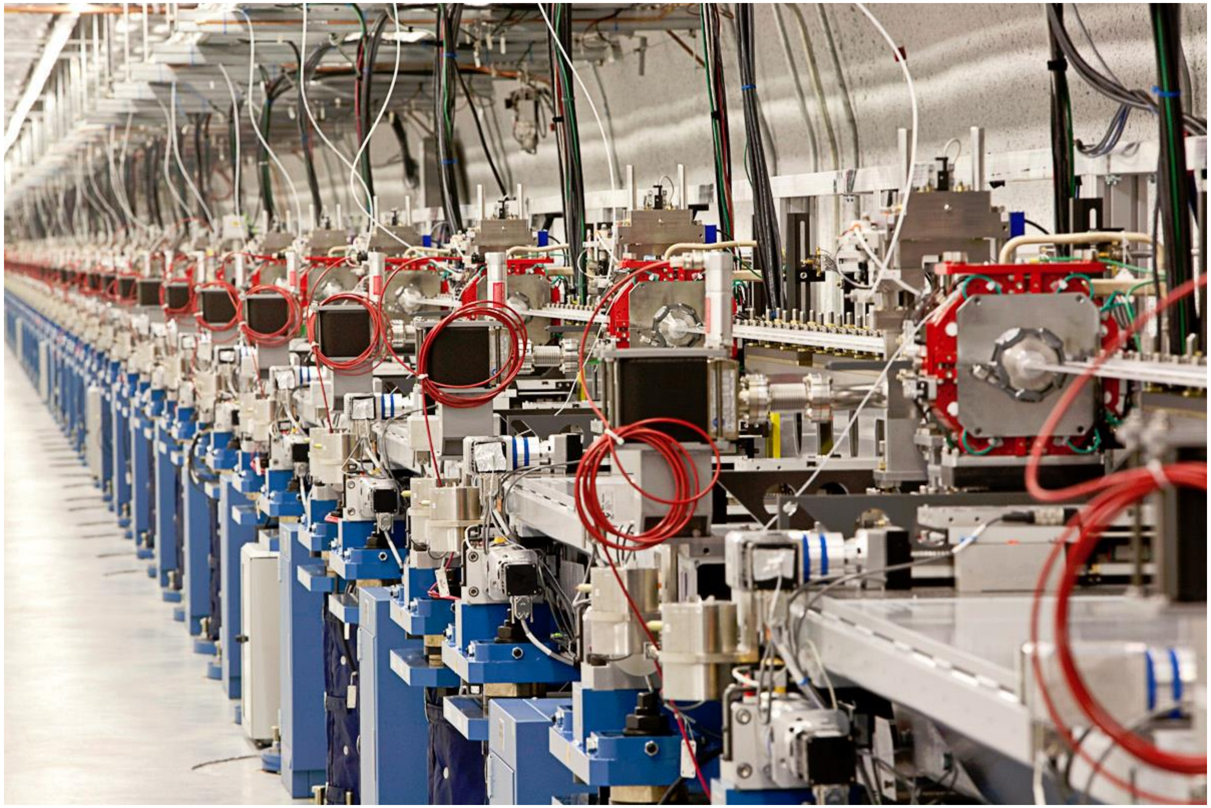
LS-SR: Max IV (Sweden, under construction)

Mag PC (3 GeV)	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (bit)	Accuracy (ppm)
Main Dip	450 - 750	145 - 210	±10	±10	16	±100
Dip strip	175	44 - 80	±1000	±1000	16	±1000
Quad	44 - 85	9 - 44	±100	±100	16	±1000
Sxtp	66 - 86	8 - 20	±100	±100	16	±1000
Octp	58 - 217	45 - 104	±100	±100	16	±1000
Corr SR	±5	±8	±25	±25	18	

- ✓ 3 GeV
- ✓ 528 m circumference
- ✓ About 1000 Power converters (overall)
- ✓ Full Energy Linac Injector
- ✓ Two SR (1.5 and 3.0 GeV)

LS-FEL: LCLS (SLAC, USA, first beam 2009)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)
Intermediate PS	Up to 375	Up to 200	100 rms	100 rms
Corr	±6 - ±30	±40	400 rms	30 rms



- ✓ 13,6 GeV
- ✓ 1000 m length

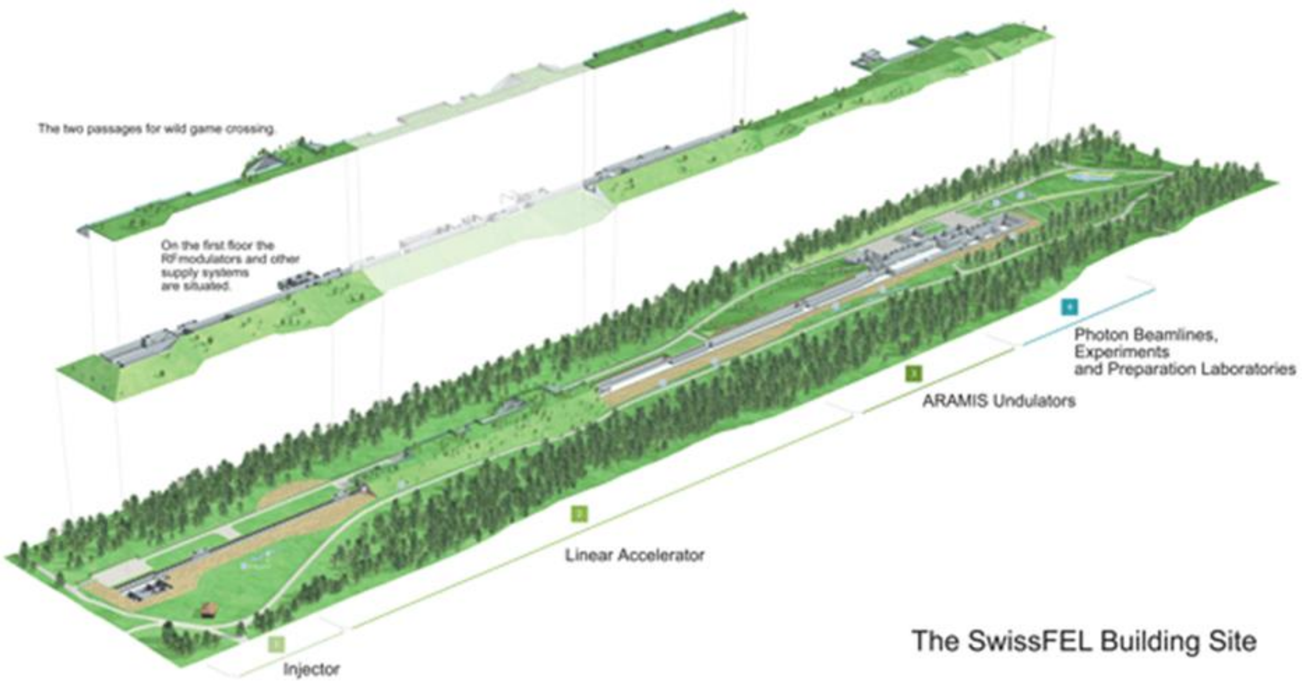
LS-FEL: FERMI (Italy, first beam 2011)

Mag	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (bit)
Dipoles	50 - 750	15 - 55	500	100	16
Q	5 - 100	10 - 30	25 - 500	10 - 100	16
Corr	±5 - ±20	±10 - ±20	25 - 30	10 - 15	16

- ✓ 1.5 GeV
- ✓ 360 m length
- ✓ 400 Power Converters
- ✓ 37 types of magnets
- ✓ 17 types of PC (2 cover 88%)

LS-FEL: SwissFEL (PSI, CH, under Construction)

Type	Iout (A)	Vout (V)	Ripple [10 Hz – 30 kHz] (ppm)
1-Quadrant IGBT	220	40-100	50
4-Quadrant IGBT	±150 - ±200	±40 - ±1100	3.5 - 50
4-Quadrant MOSFET	±10 - ±50	±10 - ±20	10 - 100



The SwissFEL Building Site

- ✓ 2.1 – 5.8 GeV
- ✓ 740 m length
- ✓ 600 Power Converters
- ✓ Feedback System for correcting slow drift
- ✓ Absolute Accuracy not a key factor

LS-FEL: XFEL (DESY, D, under Construction)

Note	Type	Iout (A)	Vout (V)	Ripple (Vout rms)	Accuracy (ppm)	Res'n (bit)
SCR	Main	600 - 800	200 - 350	1% f.s.	100	20
PWM	Chopper	200 - 600	60 - 120	1.5 - 3	100	20
PWM	Small Main	5 – 10	40 - 60	2 - 3	100	20
PWM	Correctors	±5 - ±10	±40 - ±60	2 - 3	100	20

- ✓ 17.5 GeV (up to 20 GeV)
- ✓ 3.4 km length
- ✓ Super Conductive Linac
- ✓ Mix of technologies and topologies
- ✓ Fully digital regulation (analog for correctors)

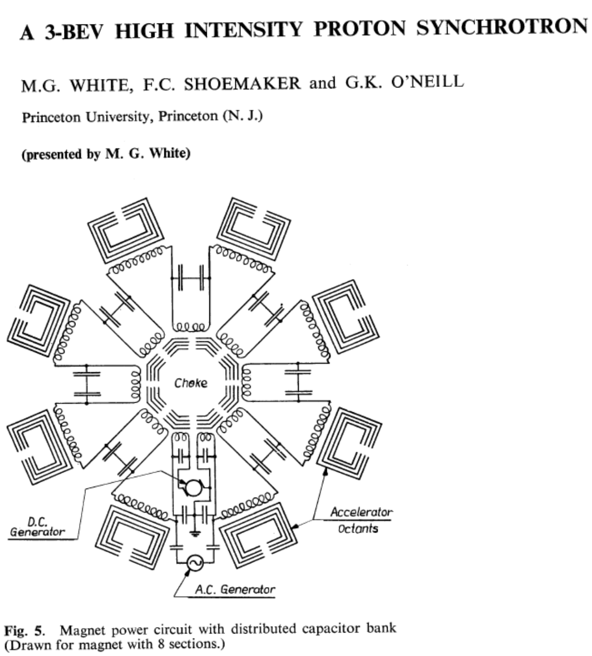
Light Sources – Booster Synchrotrons

“White Circuit” (since 1956)

- ✓ Two (AC + DC) Power Converters
- ✓ Resonating Circuit - sinusoidal
- ✓ “High” frequency (10 Hz, 12 Hz)
- ✓ High Voltage

“Direct Ramping” (after1998)

- ✓ Direct connection to Power converter
- ✓ Not-Sinusoidal ramping
- ✓ “Low” frequency (1 Hz, 3 Hz)
- ✓ “Low” Voltage

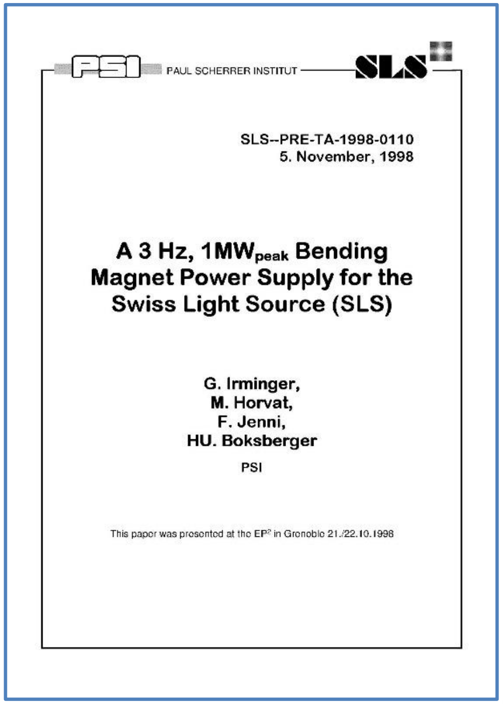

A 3-BEV HIGH INTENSITY PROTON SYNCHROTRON

M.G. WHITE, F.C. SHOEMAKER and G.K. O’NEILL

Princeton University, Princeton (N. J.)

(presented by M. G. White)

Fig. 5. Magnet power circuit with distributed capacitor bank (Drawn for magnet with 8 sections.)


PSI PAUL SCHERRER INSTITUT SLS

SLS--PRE-TA-1998-0110
5. November, 1998

A 3 Hz, 1MW$_{peak}$ Bending Magnet Power Supply for the Swiss Light Source (SLS)

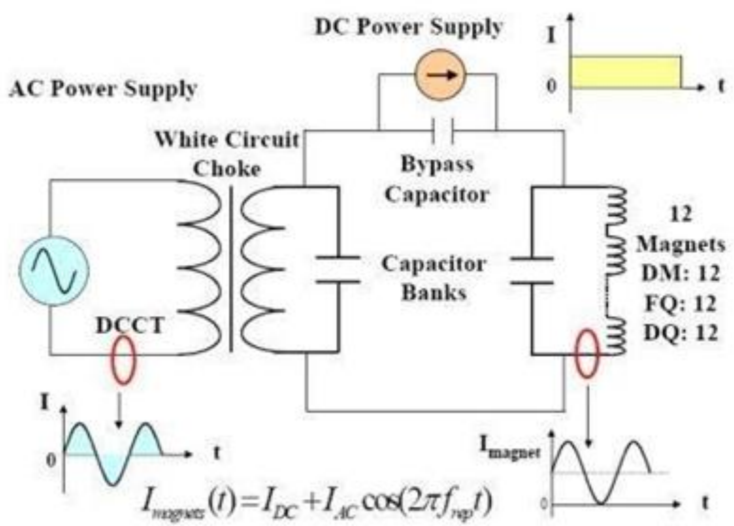
G. Irminger,
M. Horvat,
F. Jenni,
HU. Boksberger
PSI

This paper was presented at the EP² in Grenoble 21./22.10.1998

Light Sources – Booster Synchrotrons

“White Circuit”

- ✓ BESSY II (HZB, D, 1998)



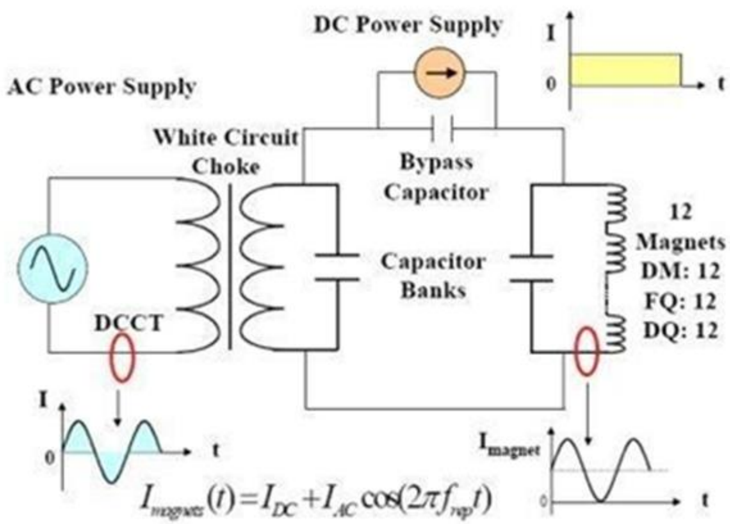
“Direct Ramping”

- ✓ SLS (Switzerland, 2000)
- ✓ LNLS (Brazil, 2001)
- ✓ Soleil (France, 2005
- ✓ DLS (UK, 2005)
- ✓ Elettra (Italy, 2007-2008)
- ✓ ALBA-CELLS (Spain, 2010)

LS-BS: BESSY II (HZB, D, 1998)

Type	Iout (A)	Vout (V)	Long Term (ppm)	Peak Values on Magnet Circuit
Dipole AC	778	311		2277 A / 3112 V @ 10 Hz
Dipole DC	1375	120	±20	
Quad AC	200	184		492 A / 527 V @ 10 Hz
Quad DC	340	70	±20	

"White Circuit"



LS-BS: SLS (PSI, CH, 2000)

Type	Iout (A)	Vout (V)	Short Term (ppm)	LongTerm (ppm)
Dipole	950	±1000	10	100
Quadrupole	140	±120	100	100

- ✓ Repetition rate: 3Hz
- ✓ First fully digital control for all Power converters of an accelerator
- ✓ 100 MeV to 2.7 GeV
- ✓ 1 PC for all dipoles in series

LS-BS: LNLS (Brazil, 2001)

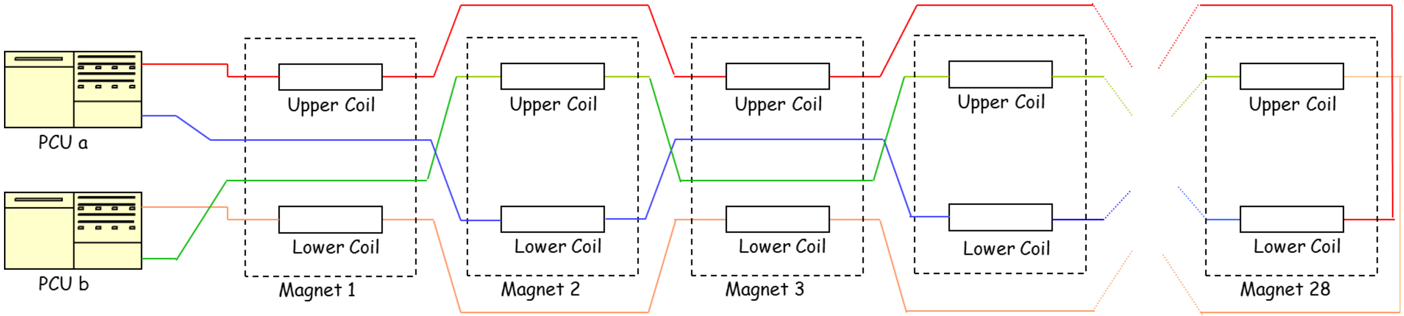
Type	Iout (A)	Vout (V)	Short Term (ppm)	Ripple (mA)
Dipole	300	420	10	±120
Quadrupole	10	21	10	±10
Sextupole	10	26	10	±10
Correctors	±5 - ±6	±10	10	±1

- ✓ Repetition rate: 1 pulse / 6 seconds
- ✓ 120 MeV to 500 MeV
- ✓ The Booster operates also as a SR

LS-BS: SOLEIL (France, 2005)

Type	Iout (A)	Vout (V)	Accuracy (ppm)	PC Number
Dipole	±580	±1000	50	2
Quadrupole	±250	±450	50	2
Sextupole	±30	±30	50	2
Correctors	±1.5	±2.5	50	44

- ✓ Repetition rate: 3 Hz
- ✓ 100 MeV to 2.75 GeV
- ✓ Dipoles in series but “split” on 2 PC
  - Peak voltage ≤1000 V



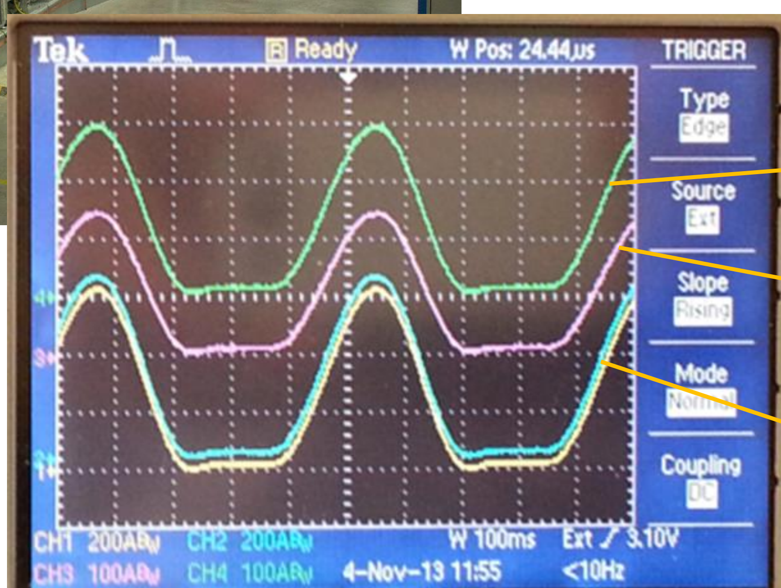
LS-BS: DLS (UK, 2005)

Type	Iout (A)	Vout (V)	Reproducibility (ppm)	Resolution (ppm)	PC Number
Dipole	1000	±2000	±50	±4	1
Quadrupole	200	±421	±50	±4	2
Sextupole	20	±60			2

- ✓ Repetition rate: 3 Hz (5 Hz Max)
- ✓ 100 MeV to 3 GeV
- ✓ Dipoles in series, 1 power converter
- ✓ Modular design

LS-BS: Elettra (Italy, 2007-2008)

Type	Iout (A)	Vout (V)	Accuracy (ppm)	PC Number
Dipole	800	±1000	±15	2
Quadrupole	±400	±400	50	2
Sextupole	±35	±35	50	2



Iout PSQD

Iout PSQF

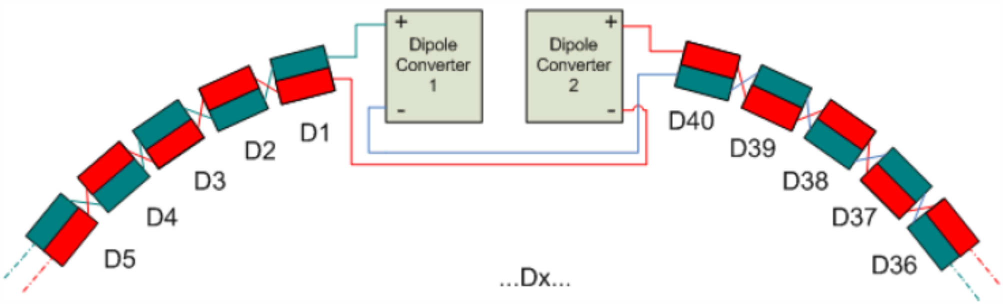
Iout PSB1 & PSB2

- ✓ Repetition rate: 3 Hz
- ✓ 100 MeV to 2.5 GeV
- ✓ Dipoles in series but “split” on 2 PC
  - Peak voltage ≤1000 V

LS-BS: CELLS-ALBA (Spain, 2010)

Type	Iout (A)	Vout (V)	Stability (ppm)	Resolution (ppm)	Reproducibility (ppm)	PC Number
Dipole	±750	±1000	±15	5	±50	2
Quadrupole	±180	±120 - ±750	±15	5	±50	4
Sextupole	±8	±70	±50	15	±100	2
Correctors	±6	±12	±50	15	±100	72

- ✓ Repetition rate: 3 Hz
- ✓ 100 MeV to 3 GeV
- ✓ Dipoles in series but "split" on 2 PC
  - Peak voltage ≤1000 V



Remarks and Conclusions

- ✓ Few examples from a vast world of PCs
- ✓ Clear differences among Accelerators' applications
  - Maximum current
  - Output current stability
  - Output current reproducibility
  - Output current accuracy
  - Output current di/dt (dynamics)
- ✓ Same application, different requirements
  - Accelerator type
  - Accelerator age
  - New technologies in PC field (components, low-level control, and local control)
  - New technologies in feedback and remote control fields (higher level)

Example: Storage Rings' Corrector power supplies

Storage Rings' Corrector power supplies

Facility	Iout (A)	Vout (V)	Long Term (ppm)	Ripple (ppm)	Res'n (bit)	Type
Elettra (1993)	±16	±80	±500	±50	16	Bipolar Linear
APS (1995)	±150	±20	±30	±1000	13	
LNLS (1997)	±10	±10	±1000	±100	16	Bipolar Linear
SLS (2000)	±7	±24	100	15	18	PWM
Soleil (2006)	±7 - ±14	±3.5 - ±14	20 - 50		16 - 18	PWM
DLS (2006)	±5	±20			18	PWM
ALBA (2010)	±12	±60	±20	10	18	PWM
Max IV (…)	±5	±8	±25	±25	18	PWM

Strong integration in particle trajectory/orbit feedback systems:

- Fast particle beam position monitors (detectors)
- Fast connection to control systems
- Real-time environment
- …

Acknowledgments

- ✓ My colleagues of the Power Supplies Laboratory at Elettra

- ✓ Colleagues from Facilities worldwide (private comm.):

  H.-J. Eckoldt (DESY), K. Holland (FRIB), R. Kuenzi (PSI), S. Murphy (ISIS), R. Petrocelli (ALBA), C. Rodriguez (LNLS), P. Tavares (MaxIV), J. Wang (APS)

- ✓ Power Converter Companies (Not Traceable info!)
  - Bruker/SighmaPhi Electronics
  - EEI
  - OCEM

References

- ✓ Facilities' web sites
- ✓ Joint Accelerator Conferences Website
  http://www.jacow.org/index.php?n=Main.Proceedings
- ✓ Wikipedia
  http://en.wikipedia.org

More sources (not free)

- ✓ *IEEEXplore Digital Library*
  http://ieeexplore.ieee.org/xpl/conferences.jsp (available for IEEE members or purchase)
- ✓ European Power Electronics And Drives Conferences
  http://www.epe-association.org/epe/index.php (available for download to EPE members)

Thank you!

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