1 ALBA POWER CONVERTERS PRESTUDY

1.1 USER REQUIREMENTS

The power converters concerned are those of the Booster accelerator and transfer lines. Every 20 minutes there are approximately 12 cycles of beam acceleration and extraction. Each acceleration and extraction cycle lasts 1/3 of a second.

1.1.1 Booster Bending magnets

The booster bending magnets are powered by two power converters. Each of the upper and lower magnet coils is connected to a different converter. The series connected coils represent a load of 0.355Ohm and 100mH.

The magnetic cycle is in the form of a sinewave. A conceptual cycle representation appears in Figure 1. The peak current is 700A.

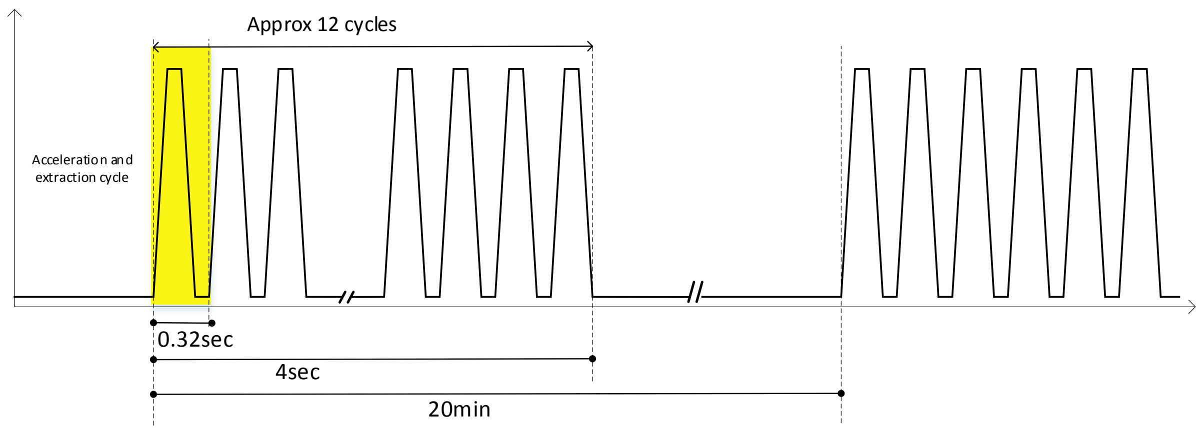


Figure 1: Booster machine bending magnet cycles. Each current cycle corresponds to an acceleration and extraction of a beam.

A single extraction event is assumed (<5usec duration) during flat-top as seen in Figure 2. The blue line represents a sinusoidal form used in the ALBA booster magnets and the black trapezoidal waveform represents an "equivalent" waveform used for the analysis. Note that since beam injection takes place at around 10-20ms the beam rather sees the linear part of the sinusoidal.

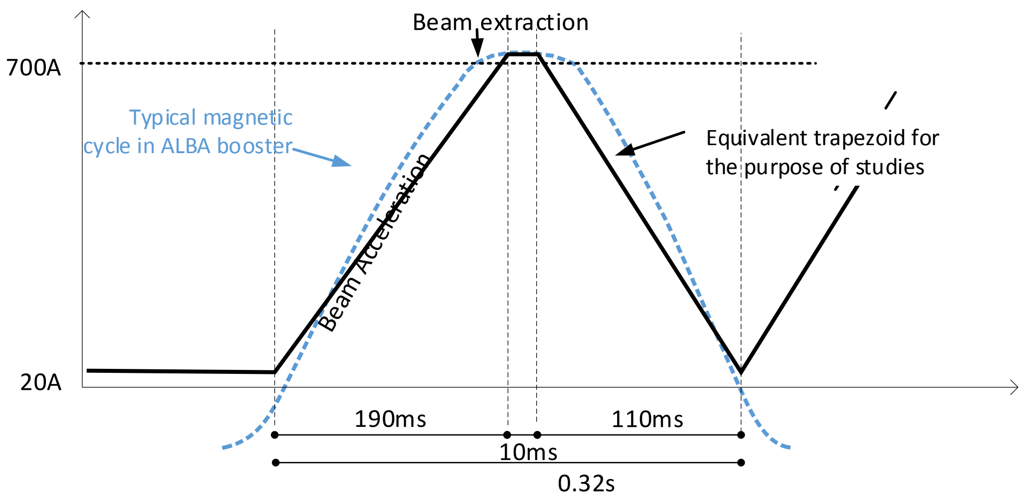


Figure 2: Detail of one acceleration-extraction cycle. An equivalent trapezoid waveform (in black) is used for the study. This waveform corresponds to the main bending.

It can be noted (Figure 3) that the actual magnetic cycle has a rise time of 150ms from 20A to 750A which implies a higher voltage. In this study we use "worst case conditions" (rise time is 200ms).

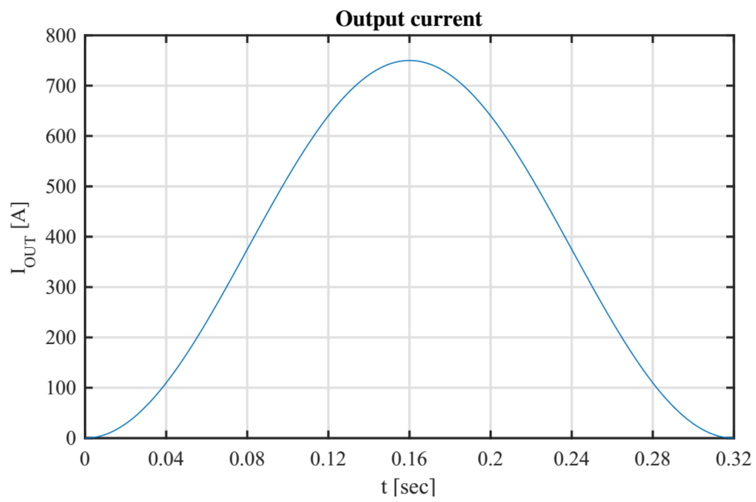


Figure 3: the actual magnetic cycle provided by ALBA

1.2 POWERING SOLUTIONS

1.2.1 Scenarios

Three scenarios are being proposed:

- the baseline scenario corresponds to the baseline requirements. Note that the Sirius Solution cannot provide continuous (DC) operation at the maximum current. The maximum DC current is noted in the following tables.
- the "baseline+" scenario allows for the possibility to power all QS180 magnets in series with a single converter and offers the associated cost saving.
- the "economy" scenario assumes the modification of the magnetic cycle period from 0.32 to 0.4s. Less voltage is required in this case.

1.2.2 Booster Bending magnets

1.2.2.1 Solution 1: baseline scenario

The table summarises the derived electrical requirements and the proposed power converter type.

Table 1: Solution 1 for bending magnets that is compliant with present operation

Quantity	Value	Unit	notes
APPLICATION DERIVED PARAMETERS			
L_{MAGNET}	0.1	H	
R_{MAGNET}	0.355	0.355	Includes 20mOhm cabling
$I_{MAGNET,sat}$	?	A	
Imin	20	A	
Imax	700	A	Converter rating: 900A
Vmax	500	V	Converter rating :900V
Energy to recover	25	kJ	1 cap bank per brick
Rise time (Tr)	0.19	Sec	
Fall time (Tf)	0.11	Sec	
Flat-top duration (Tft)	0.01	Sec	
Period time	0.32	Sec	
Current RMS 4s	410	A	See note 1
Current RMS 40s	39	A	
Current DC max	400	A	See note 2
Power Peak	350	kW	
Power 4s	59.7	kW	Converter rating: 60kW
Operating time	5700	h/annum	
Cycles	17100	Cyc/annum	See note 3
Cycles in lifetime	342000	Cycles	In 20 years
CONVERTER PARAMETERS			
Solution	2x SIRIUS 2P2S Input: 3ph, 400V, 125A, cosφ:0.93, THD:30% Output: $900V_{PK}$,$900A_{PK}$, $400A_{RMS}$, $60kW_{RMS}$, $E_{Recoverable}$:132kJ)		

Note 1: The RMS current of one cycle assuming trapezoid waveforms is 410A (higher than the 400Arms rating of SIRIUS 2P2S) during the 4seconds of cycling time. However, the actual RMS over longer intervals will be lower given the fact that the power converters only perform 12 cycles each 20minutes.

Note 2: the power converter having an front-end stage power rating of 4x15=60kW may provide limited continuous current to the ouput that depends on the resistive losses of the load. The particular load could be supplied with sqrt(60/0.355)=411A. However this value is greater than the converter output rms current rating of 400A. Hence the maximum continuous current to the specific load is 400A.

Note3: Sirius has a calculated lifetime of more than 200 million of 1.2second cycles over its lifetime. It is considered adequate for the ALBA Booster application.

1.2.2.2 Solution 2: Increment of Booster cycle time to 0.4sec

Table 2: Solution 1 for bending magnets that is compliant with present operation

Quantity	Value	Unit	Notes
APPLICATION DERIVED PARAMETERS			
L_{MAGNET}	0.1	H	
R_{MAGNET}	0.355	0.355	Includes 20mOhm cabling
$I_{MAGNET,sat}$	?	A	
Imin	20	A	
Imax	700	A	Converter rating: 450A
Vmax	450	V	Converter rating :450V
Energy to recover	25	kJ	8 cap bank per brick – note 1
Rise time (Tr)	0.22	Sec	
Fall time (Tf)	0.12	Sec	
Flat-top duration (Tft)	0.01	Sec	
Period time	0.40	Sec	
Current RMS 4s	390	A	
Current RMS 40s	41	A	
Current DC max	291	A	sqrt(30kW/0.355Ohm)
Power Peak	315	kW	
Power	53.8	kW	See note 1
Operating time	5700	h/annum	
Cycles	17100	Cyc/annum	
Cycles in lifetime	342000	Cycles	In 20 years
CONVERTER PARAMETERS			
Solution	2x SIRIUS 2P Input: 3ph, 400V, 63A, cosφ:0.93, THD:30% Output: 450V_{PK},900A_{PK}, 400A_{RMS}, 30kW_{RMS}, $E_{Recoverable}$:66kJ)		

Note1: The rms power is 53.8kW (higher than the rated output rms power of 30kW of Sirius 2P) when calculated over one magnetic cycle, howerver it is much lower over a longer integration period (ex.40s). Sirius is generally capable to supply short-term rms losses from the capacitive energy storage, that is why we propose this (pending further verifications by simulation).

1.2.3 Booster Quadrupole Magnets QS180

Two solutions are proposed; solution 1 is the baseline solution that satisfies the user requirements without modifications and solution 2 that proposes a powering modification to achieve economies by use of a single power converter.

1.2.3.1 Solution 1: Baseline scenario

Table 3: Solution 1 for bending magnets that is compliant with present operation

Quantity	Value	Unit	notes
APPLICATION DERIVED PARAMETERS			
L_{MAGNET}	0.0272	H	8 magnets in series
R_{MAGNET}	0.44	Ohm	*discrepancy with spec
$I_{MAGNET,sat}$	?	A	
Imin	0	A	
Imax	180	A	Converter rating: 450A
Vmax	81	V	Converter rating: 450V
Energy to recover	0.4	kJ	
Rise time (Tr)	0.24	Sec	
Fall time (Tf)	0.04	Sec	
Flat-top duration (Tft)	0.01	Sec	
Period time	0.32	Sec	
Current RMS 4s	102	A	Converter rating: 200A
Current RMS 40s	10	A	
Current DC max	185	A	Converter rating: 200A
Power Peak	14.6	kW	
Power 4s	4.6	kW	
Operating time	5700	H	
Cycles	17100	Cycles/annum	
Cycles in lifetime	342000	Cycles	In 20 years
CONVERTER PARAMETERS			
Solution	SIRIUS S Input: 3ph, 400V, 32A, cosφ:0.93, THD:30% Output: $450V_{PK}$,$450A_{PK}$, $200A_{RMS}$, $15kW_{RMS}$, $E_{Recoverable}$:33kJ)		

1.2.3.2 Solution 2 (baseline+): 1 converter to power all 16 magnets in series

This scenario implies that it is possible to power all quadrupoles (type QS180) using the same power converter and obviously using the same current reference.

Table 4: Solution 1 for bending magnets that is compliant with present operation

Quantity	Value	Unit	notes
APPLICATION DERIVED PARAMETERS			
L_{MAGNET}	0.0544	H	8 magnets in series
R_{MAGNET}	0.88	Ohm	*discrepancy with spec
$I_{MAGNET,sat}$	?	A	
Imin	0	A	
Imax	180	A	Converter rating: 450A
Vmax	162	V	Converter rating: 450V
Energy to recover	0.9	kJ	
Rise time (Tr)	0.24	Sec	
Fall time (Tf)	0.04	Sec	
Flat-top duration (Tft)	0.01	Sec	
Period time	0.32	Sec	

Current RMS 4s	102	A	Converter rating: 200A
Current RMS 40s	10	A	
Current DC max	131	A	Converter rating: 200A
Power Peak	29.2	kW	
Power 4s	9.1	kW	
Operating time	5700	H	
Cycles	17100	Cycles/annum	
Cycles in lifetime	342000	Cycles	In 20 years
CONVERTER PARAMETERS			
Solution	SIRIUS S Input: 3ph, 400V, 32A, cosφ:0.93, THD:30% Output: 450V_{PK},450A_{PK}, 200A_{RMS}, 15kW_{RMS}, $E_{Recoverable}$:33kJ)		

Note1: The economy scenario that assumes a magnetic cycle of 0.4sec instead of 0.33 will result in lower RMS values than the baseline+ scenario. It is therefore not further detailed for QS180.

1.2.4 Booster Quadrupole Magnets QS340

Table 5: Solution 1 for bending magnets that is compliant with present operation

Quantity	Value	Unit	notes
APPLICATION DERIVED PARAMETERS			
L_{MAGNET}	0.048	H	8 magnets in series
R_{MAGNET}	0.61	Ohm	*discrepancy with spec
$I_{MAGNET,sat}$	?	A	
Imin	0	A	
Imax	180	A	Converter rating: 450A
Vmax	115	V	Converter rating: 450V
Energy to recover	0.8	kJ	
Rise time (Tr)	0.24	Sec	
Fall time (Tf)	0.05	Sec	
Flat-top duration (Tft)	0.01	Sec	
Period time	0.32	Sec	
Current RMS 4s	105	A	Converter rating: 200A
Current RMS 40s	10	A	
Current DC max	157	A	Converter rating: 200A
Power Peak	20.7	kW	
Power 4s	6.7	kW	
Operating time	5700	H	
Cycles	17100	Cycles/annum	
Cycles in lifetime	342000	Cycles	In 20 years
CONVERTER PARAMETERS			
Solution	SIRIUS S Input: 3ph, 400V, 32A, cosφ:0.93, THD:30% Output: 450V_{PK},450A_{PK}, 200A_{RMS}, 15kW_{RMS}, $E_{Recoverable}$:33kJ)		

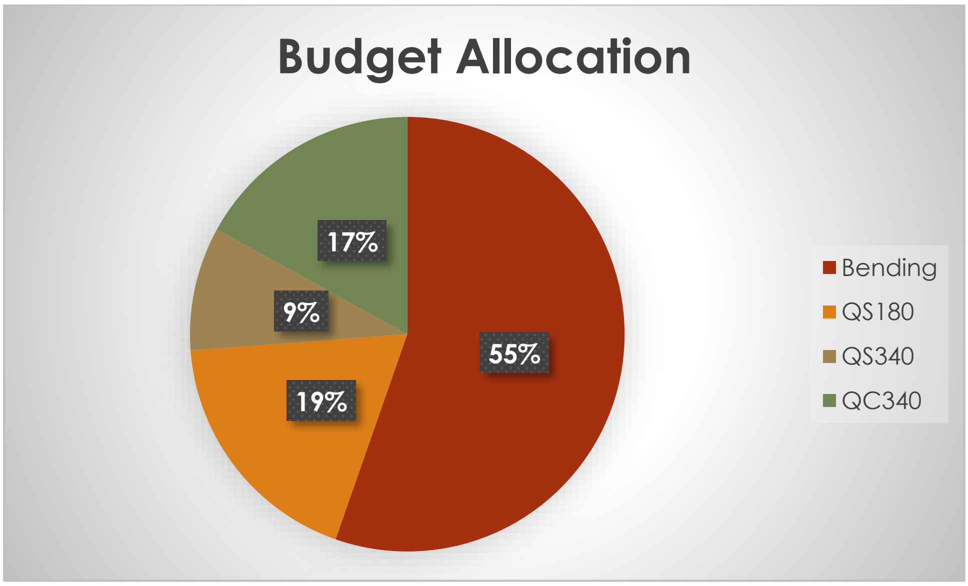
1.2.5 Booster Quadrupole Magnets QC340

Table 6: Solution 1 for QC340 that is compliant with present operation

Quantity	Value	Unit	notes
APPLICATION DERIVED PARAMETERS			
L_{MAGNET}	0.216	H	8 magnets in series
R_{MAGNET}	2.36	Ohm	*discrepancy with spec
$I_{MAGNET,sat}$	?	A	
Imin	0	A	
Imax	180	A	Converter rating: 450A
Vmax	460	V	Converter rating: 450V
Energy to recover	3.5	kJ	
Rise time (Tr)	0.24	Sec	
Fall time (Tf)	0.06	Sec	
Flat-top duration (Tft)	0.01	Sec	
Period time	0.32	Sec	
Current RMS 4s	105	A	Converter rating: 200A
Current RMS 40s	10	A	-
Current DC max	113	A	Converter rating: 200A
Power Peak	82.8	kW	
Power 4s	25.9	kW	
Operating time	5700	H	
Cycles	17100	Cycles/annum	
Cycles in lifetime	342000	Cycles	In 20 years
CONVERTER PARAMETERS			
Solution	SIRIUS 2S Input: 3ph, 400V, 63A, cosφ:0.93, THD:30% Output: $900V_{PK}$,$450A_{PK}$, $200A_{RMS}$, $30kW_{RMS}$, $E_{Recoverable}$:66kJ)		

1.2.6 Summary and Cost

A relative budget allocation is proposed as follows:



All costs include the power part, two DCCTs per converter (redundancy) and the FGC3 control crate. The costs do not include a gateway and custom controls.

1.2.7 Infrastructure requirements

Sirius must be installed on a metallic structure that allows connection of services (electricity, water and communications) from openings on the base. The following reference documens can be consulted:

- floor specification
- Installation specification

The cooling water requirements are compatible with the ALBA cooling system:

	ALBA	CERN SIRIUS
Water conductivity	0.2 µS/cm	OK
Inlet temperature	23°C±1°C	Max: 29°C
Maximum temperature variation	10°C	OK – to verify with cycles
Inlet pressure	10 bar	OK- Max 16bar
Minimum outlet pressure	4 bar	OK – max press.drop:4bar

1.3 POINTS FOR DISCUSSION

Magnet Saturation Characteristics

What is the magnetic saturation characteristics of the magnet? If for example it saturates at around half current, the maximum current could be reached even faster with the maximum voltage.

Actual waveforms

TO have a definite suitability check for Sirius a more precise representation of the magnetic cycle is needed. The duration of the acceleration part and of the extraction part are needed.

Magnetic cycle waveform

Would the machine be able to cope with trapezoid magnet current waveforms with a flat-top extraction plateau? This would allow best utilization of the power converters to reduce the RMS current. It would also probably permit a better reproducibility during extraction.

Additionally a scenario that would further relax the converter specifications and would result in energy savings is using a fast ramp down with maximum voltage regardless of the cycle. It is assumed that there is no physics operation during ramp-down. The following figure illustrates this concept.

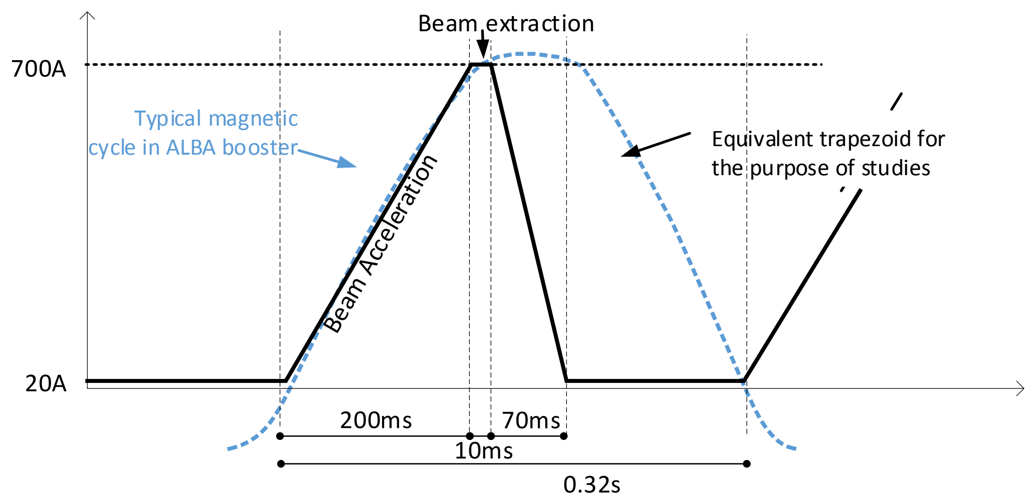


Figure 4: After physics operations end the current can be reduced to 0 with the maximum voltage applied

Booster utilization

The ALBA Booster seems to be Idle for a large portion of the time. If its cycling period could be increased from 0.33sec to approx. 0.4sec the magnetic cycles could be achieved with just 450V across each bending magnet circuit. That would reduce the requirement from a SIRIUS 4PS to a SIRIUS 2P (P_{out}=24kW, Energy recovery 25kJ (=4 capacitor banks) and $I_{RMS,out}$=263A, $I_{max,out}$=700A) and would result in approximately half the cost.

1.4 REFERENCES

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