ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS049

ENERGY COMPARISON OF ROOM TEMPERATURE AND SUPERCONDUCTING SYNCHROTRONS FOR HADRON THERAPY

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Abstract

The yearly energy requirements of normal conducting (NC) and superconducting (SC) magnet options of a new hadron therapy (HT) facility are compared. Special reference is made to the layouts considered for the proposed SEEIIST facility. Benchmarking with the NC CNAO HT centre in Pavia (Italy) was carried out. The energy comparison is centred on the different synchrotron solutions, assuming the same injector and lines in the designs. The beam current is 20 times higher than present generation facilities: this allows efficient multi-energy extraction (MEE), which shortens the therapy treatment and is needed especially in the SC option, because of the slow magnet ramping time. Hence, power values of the facility in the traditional mode were converted into MEE ones, for a fair comparison between NC and SC magnets. cryocoolers (c.c.) and a liquefier are also compared, for synchrotron refrigeration. This study shows that a NC facility in MEE mode requires the least average energy, followed by the SC synchrotron solution with a liquefier, while the most energy intensive solution is the SC one with c.c.

INTRODUCTION

Radiotherapy is a fundamental component of effective cancer treatment. Radiation therapy with protons and other ions, also called hadron therapy (HT), offers several advantages over the classical RT with X-rays. Nowadays, HT has reached the time of transitioning from a limited number of specialized institutions to many particle therapy centres worldwide. In 2018, the conceptual study of a new ion therapy and research facility in Southeast Europe was proposed [1]. It consists in an advanced version of the PIMMS design [2], accelerating beams of p (up to 250 MeV), $^{4}He^{2+}$, $^{12}C^{6+}$ and heavier nuclei (up to 430 MeV/u), with 20 times more beam current than present generation machines. It will work in MEE mode [3], with the possibility of a single-turn extraction (10^{10} ions in ~1 us) to perform FLASH therapy [4]. For the SEEIST facility, the gantry is assumed to be superconducting (SC) [5], while for the synchrotron both the room temperature (RT) and superconducting (SC) versions are studied. A SC synchrotron is certainly more compact than a RT one (see Fig. 1 and Table 1). This paper provides a first evaluation of the average power required by the whole SEEIIST facility, comparing the RT and SC synchrotron cases.

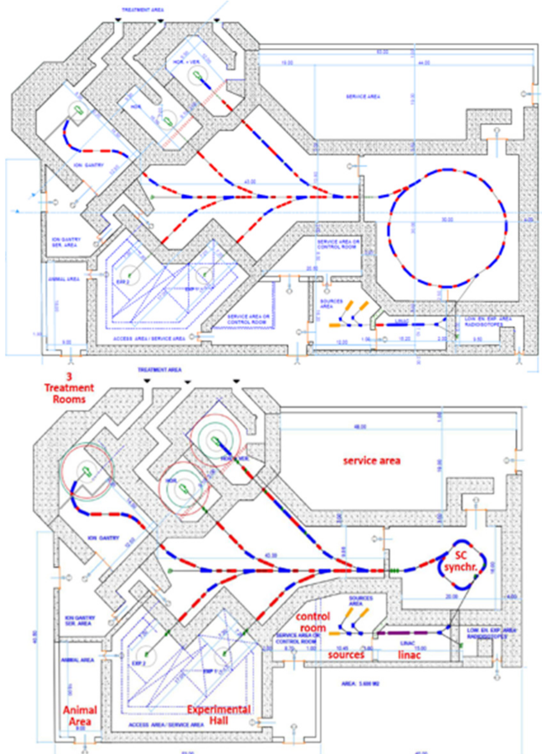

Figure 1: Layout of the SEEIST RT facility (16 dipole synchrotron, left) and the SC one (4 dipoles).

Table 1: Main Specifications of the RT and SC Synchrotrons (for $^{12}C^{6+}$)

	RT synchrotron	SC synchrotron
Energy	430 MeV/u	430 MeV/u
Circumference	70 m	27 m
$(B\rho)_{max}$	6.62 Tm	6.62 Tm
B_{max}	1.5 T	3.5 T
ρ	4.23 m	1.89 m
Ramp rate	2.4 T/s	1 T/s

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS049

The two options, differing by the synchrotron layout, have in common the RT linac injector, injection and extraction systems, the beam lines and the SC gantry.

THE CNAO FACILITY AS BENCHMARK

The calculation of the energy consumption of any accelerator facility is based on the electric characteristics of the most energy-intensive components, as well as on the setting corresponding to their average power and their operational duty cycle. The former can be derived from the machine specs, while the latter require explicit hypotheses on their realistic operation modes. The CNAO facility [6]. in Pavia ($E_{12\text{-}C}$=400 MeV/u) has technical specifications which are largely like the SEEIIST RT option: to benchmark the calculation method, we used them to calculate the consumption of the whole facility and compared a qualified portion of it with the measured energy supply at the technological station.

The CNAO injector, based on an RFQ and an IH-DTL (E_{fin}=7 MeV/u), is kept on at a RF d.c.=0.5% for 93% of the year (off only during long maintenance periods). Averaging the consumption over 1 year delivers an yearly-averaged power $P_{av,yr}$~66 kW. Waiting for an upgrade linac design to be completed, this value has been used for the RT and SC SEEIST layouts too.

The CNAO synchrotron, because of the beam current limitations from the injector, was not designed to be operated in the MEE mode: its magnets are ramped-up and down for each of the energy values required by the treatment plan. Table 2 shows the synchrotron elements, with the electrical specifications required to calculate $P_{av,yr}$. $P_{max\text{-}T,all}$ values (electric power at the maximum current) are corrected upwards to include the power converter (p.c.) efficiency ($P_{maxT,all,plug}$), and downwards, considering the average value of the electrical power, consistent with the actual energy value at which the machine is operated ($P_{typ\text{-}T,all}$, see next paragraph). This value is further reduced by the use fraction of the machine for protons (10.8%) and carbon ions (13.4%) and by the cycle time fraction in which the machine is at the flattop. Overall, $P_{av,yr}$~90 kW for the synchrotron. Powering the extraction septa in pulsed mode has been proposed for the next machines [7].

Table 2: Calculation of the CNAO Synchrotron Average Power from the Electrical Specs and the Duty Cycle

	Synchrotron elements	N	R [Ω]	$I_{max\text{-}T}$ [A]	$P_{max\text{-}T,1}$ [kW]	$P_{max\text{-}T,all}$ [kW]	$\varepsilon_{p.c.}$	$P_{max\text{-}T,plug}$ [kW]	$P_{typ\text{-}T}$ [kW]	Yearly d.c.	CW-equiv. power	$P_{av,yr}$ [kW]
^{12}C	Dipoles (17 in 1 series)	1	0,08	2778	617,38	617,38	0,70	882,0	541,91	13,4%	47,2%	34,3
	Qpoles (24 in 3 families)	3	0,166	540	48,41	145,22	0,89	163,2	100,25	13,4%	47,2%	6,3
	Sext. 2x2 familes	2	0,067	500	16,75	33,50	0,90	37,2	22,87	13,4%	47,2%	1,4
	Resonance sextupole	1	0,039	500	9,75	9,75	0,70	13,9	8,56	13,4%	47,2%	0,5
	Inj. m. Septa (series of 2)	1	0,0044	3889	66,54	66,54	0,58	114,7	114,73	13,4%	100%	15,4
	Extr.m.s. type-1 (series of 3)	1	0,014	3479	169,45	169,45	0,77	220,1	135,21	13,4%	100%	18,1
p	Dipoles (17 in 1 series)	1	0,08	2778	617,38	617,38	0,70	882,0	57,41	10,8%	49,8%	3,1
	Qpoles (24 in 3 families)	3	0,166	540	48,41	145,22	0,89	163,2	10,62	10,8%	49,8%	0,6
	Sext. 2x2 familes	2	0,067	500	16,75	33,50	0,90	37,2	2,42	10,8%	49,8%	0,1
	Resonance sextupole	1	0,039	500	9,75	9,75	0,70	13,9	0,91	10,8%	49,8%	0,0
	Inj. m. Septa (series of 2)	1	0,0044	1745	13,40	13,40	0,58	23,1	23,10	10,8%	100%	2,5
	Extr.m.s. type-1 (series of 3)	1	0,014	1417	28,11	28,11	0,77	36,5	2,38	10,8%	100%	0,3
Others	Dipole washout for p											6,79
	Dipole washout for 12C											0,56
	RF cavity (Medaustron)	1				4,0	0,75	5,3	5,5%			0,30
TOTAL (Synchrotron)												**90,3**

With the same method adopted for the synchrotron, $P_{av,yr}$ for the three beam lines (2 horizontal, 1 horizontal+vertical) was calculated too, knowing that the field in the magnets does not cycle, but changes in steps – at the end of each machine cycle – according to the change in the beam energy. $P_{av,yr}$~90 kW for the beam lines, where the large vertical dipole counts for 1/3 of the total. Finally, consumption of the p.c. in idle state, vacuum pumps and beam instrumentations are added ($P_{av,yr}$~47 kW in total), with 30% of the total for the cooling power. $P_{av,yr}$~346 kW is the total for the CNAO facility.

As to the operational data, those data provided for one year of operation at CNAO were assumed as a general reference in the energy comparison of the two SEEIIST layouts considered. Fig. 2 shows the distribution of the beam energies, for p and ^{12}C, in one year at CNAO.

It is to be noted (as shown in Table 2) that the effective total use of the synchrotron was only 24.2%, a value confirmed experimentally and checked for consistency with another therapy centre.

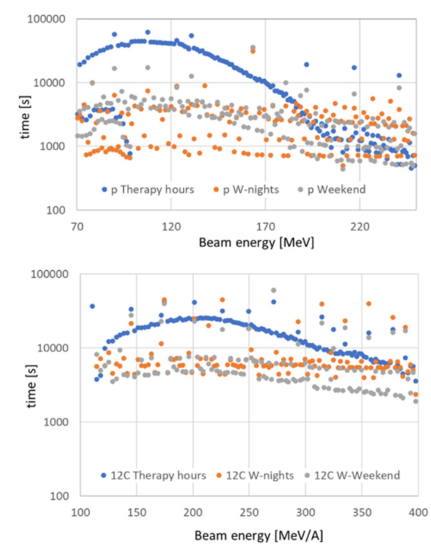

Figure 2: Time distribution vs. E_{beam} of proton and carbon beams during typical year 2020 of operation at CNAO.

Considering the increase of the maximum ^{12}C energy, the CNAO-statistics in the use of the facility (Fig. 2) has been applied to the RT and SC layouts (see next paragraph).

The electric cabin instrumentation can supply an approximate measurement of the $P_{av,yr}$ contributed by the time-variable part of the accelerator (~235±20 kW). The corresponding value, calculated as done above from the electrical specs and the duty cycle, is 193 kW. Given the approximation, this comparison confirms the adopted calculation approach rather well.

THE SEEIIST RT FACILITY

The RT SEEIIST facility, versus the CNAO one, offers $E_{12\text{-}C,max}$=430 instead of 400 MeV/u; 20 times higher beam current and MEE operation; larger fraction (65 vs 40%) of the time planned for experimental tests; 5 beam lines, 1 of which equipped with a SC gantry.

The slightly larger final energy can be achieved by the same p.c. of CNAO, of which it can keep the electrical specifications, increasing the p.c. output current. The beam

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lines, realised with more modern p.c., have better specifications as to energy consumption. The MEE mode shortens the treatment time by eliminating large fractions of the dead time between successive energy steps, but keeps the synchrotron magnets at full field during the ~ 200 ms energy changes, delivering a modest 14% $P_{av,yr}$ reduction.

The SC gantry [8], with 5 SC combined function dipoles (3 T field for the dipole and 3,5 T/m quadrupole gradient), 3 SC quadrupoles (40 T/m) and 7 room-T quadrupoles (25 T/m), features overall transient losses of 2 W/m at 4.2K of the dipoles (7 m total length), for a total of 14 W. To this the contribution of the SC quadrupoles (4 W) must be added, together with the static consumption of the cryostats (2 W, with 0.3 W/m) and the contribution of the current leads (2 W, at ~ 0.1 W/kA). The total power of 22 W at 4.2K can be removed by 11 double-stage c.c., consuming 7 kW at the plug each, delivering $P_{c.c.}$~ 77 kW in total, to which the $P_{av,yr}$ of the RT magnets (4 kW) must be added. In conclusion $P_{av,yr}$ ~ 81 kW for the gantry.

Calculations similar to those done for CNAO, applied to the RT version of the SEEIST facility of Fig.1, deliver a total $P_{av,yr}$ ~379 kW.

THE SEEIIST SC FACILITY

The SC option differs from the RT one in the synchrotron. Energy consumption occurs in the field ramps and is virtually zero in the plateaus. With MEE, it is necessary to sum the contributions of each individual field from the minimum field to the maximum magnetic field and backwards. A reference for the energy consumption of ramped SC magnets is the prototype realized in the DISCORAP experiment at INFN [9] (3.9 m long dipole, B_{max}=4.5 T, $\frac{dB}{dt}$ =1 T/s). The largest contribution (two thirds) to the losses is the persistent current in the superconductor $P_{sp} = M_{pc}\dot{B}$, where M_{pc} is the magnetization. Interpolating the pc vs B in the conductor with a power function (in Fig. 3 the graph and the displayed equation), allows to integrate it between the field extremes 0.4 and 3.5 T:

$$U_{sp,ramp} = \int_{tmin}^{tmax} P_{sp} dt = \int_{t_{min}}^{t_{max}} P_{sp} \mathrm{dB} \left(\frac{dB}{dt}\right)^{-1}$$

A full ramp for C ions, covering the 0.4÷3.5 T range, requires $U_{sp,ramp}$~13 J/m at 4.2K. The contribution of the coil ends, and of all other losses in %, were then added.

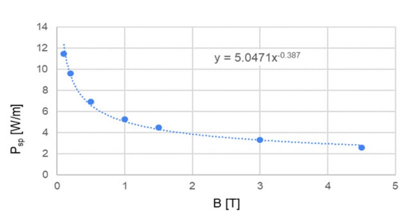

Figure 3: power-per-meter vs. B (T) at 4.5K required by the straight section of the DISCORAP magnet.

Knowing the energy of all treatments administered to patients in 2020, the corresponding SC dipole field and the energy required at 4.2K is obtained, i.e. ~1 W. The static load of the cryostat (3.6 W), gives $P_{av,yr}$ (4.2K) ~4.6 W.

This would be the reference number, if the dissipation were constant in time. However, dissipation is rather concentrated in the ramp-down to ramp-up periods of the dipoles, from one MEE to the next. It is mandatory not to exceed the critical temperature (T_C) of the magnet in those time spans. From CNAO statistics, the most critical case are the short ramps (achieving smaller B_{max} values, on the more dissipative part of Fig.3), followed by short quasi-flattops for MEE. For each dipole, this corresponds to P=14 W for a period dt=2.2 s, with additional 0.15 W loss in the subsequent 50 s, before the next MEE starts. With c.c. able to remove 2 W each from a Cu-mass (c_p=0.1 J/kgK being the Cu specific heat at 4.2K), estimated in m=400 kg, with ΔT=0.3K, to stay at least 1K away from T_C (5.5K at 3.5 T), the number of needed c.c. (N_{cc}) is derived from

$$[P - N_{cc}(2\ W)] \leq mc_p\Delta T$$

giving N_{cc}=4 per dipole, plus 1 c.c. for the static load. With 7 kW/cc, the total plug power for the SC dipoles would be 140 kW, a practical (ease of maintenance) but inefficient solution. As alternative, a commercial refrigerator [10] – of more demanding maintenance - may provide 130 W refrigeration power at 4K (with liquid nitrogen precooling) with a plug power of 45 kW only.

For the SC solution, the energy contributions of the p.c., warm cables, busbars, etc. must be added, together with all the RT elements of a typical, albeit smaller, synchrotron.

$P_{av,yr}$ (SC facility) ~522 kW with c.c. and ~400 kW with a refrigerator. Last, it must be noted that future SC septa [11], would be cooled by the refrigerator, together with the magnets at no additional power (36 kW less in $P_{av,yr}$).

CONCLUSION

After benchmarking the calculation method on CNAO data, we calculated the $P_{av,yr}$ of a fully RT facility and a facility where the synchrotron is SC. The results are summarised in Table 3. We note: that the overall average power is not huge ($P_{av,yr}$ ~ 0.5 MW), the RT solution being the one with the lower and the SC one (with c.c.) the one with the higher electricity bill. On the other hand, at equal energy consumption (NC and SC with liquefier being very close) the SC solution requires a smaller installed power.

Table 3: Yearly Average Power (in kW) of the 3 Options

Options	RT	SC (c.c.)	SC (refr.)
Linac	68,4	68,4	68,4
Synchrotron	76,0	192,0	97,0
Beam Lines	14,4	14,0	14,0
Others	80,3	80,3	80,3
SC Gantry	47,4	47,4	47,4
TOTAL	**286,3**	**402,1**	**307,1**
Cooling	85,9	120,3	91,8
Grand total	**372,2**	**522,4**	**398,9**

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