GSI Report 04. .12. 1996

Strategy for Achieving High Target Power Density with a Modified SIS 18 and the New High Current Injector (U^{28+})

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Introduction

We develop a strategy and list the requirements of how to achieve the full potential of SIS 18 for performing plasma and radiation physics experiments.. The basis is the status as it will exist in 1999, plus a fast-buncher cavity which has been already foreseen, and for which space in the ring is still reserved. Plasma experiments can also be done with modest fast bunching, using the existing RF cavities, The attainable target power densities are then much lower than listed in table III. These preliminary modes of operation are not detailed in this paper.

We have to consider two operational modes, depending on the requirements of the target. Surely the single-turn-injection mode gives the higher power density in a small target. The beam would, for instance, fit through a small opening in a radiation hohlraum. In the multi-turn-injection mode a higher total beam energy is accumulated, which finally (because of lower phase-space density) is spread over a larger target mass in a longer beam pulse.

For attainig the potential limit of present SIS 18 for generating dense plasmas (≈ 3 TW/g, ≈ 10 eV), we need

- the high-current Unilac upgrade under construction, delivering U^{28+} beams with an intensity of the order of 10 mA;
- no ion stripping between linac and SIS;
- a slight widening of the frequency range of the SIS ferrite cavities down to 0.5 MHz, or an extra 0.5 MHz fixed-frequency ferrite cavity;
- a powerful fast-buncher cavity to compress the bunch longitudinally, on about 1.5 MHz.

We attempt to make use of the electron cooler under construction for ion velocities up to 60 MeV/u. If cooling at higher energies turns out to be possible, one should use it. We anticipate this by studying parameters with cooling at 73.7 MeV/u (electron energy 40 kV), for then the ion velocity is just 2/3 of the maximum velocity at 18 Tm. Before the fast-buncher cavity is built, the energy limit of the electron cooler must be determined, because this influences the choice of frequency. (We intend to keep both options, cooled and uncooled beam, open without a change of hardware, especially of the bunching cavity.) If the velocities are lower, all the energy, power, energy density and power density figures in table III have to be degraded slightly.

The transfer line from the linac to SIS should contain an active debuncher, and a linac-frequency cavity (a few kV) should be installed in the ring. This additional cavity can be used to attain the best possible momentum definition in the single-turn injection mode.

Keil-Schnell-limit:

$(\Delta p/p)_o \geq 4 \cdot 10^{-4}$ (coasting beam)

This limit can be attained only with an extraordinarily good performance of the linac (e. g. 20 turns with 13 mA, or 21 turns with 12 mA). So our calculations have to be regarded as optimistic (half of it is realistic). Ideally the linac should have a somewhat higher final energy.

2. Synchrotron Acceleration

Acceleration can be done at any suitable revolution harmonic if after acceleration the beam is debunched for cooling and for recollection in one bunch. If not, and if bunch merging is tried, the harmonic should be 2^n, any integer n.

2.1 Acceleration to an energy adequate for cooling

Parameters:

E_k/A = 73.7 MeV/u (to meet the 3[rd] subharmonic of the envisaged buncher cavity)

$\beta\gamma$ = 0.4056

BR = 10.712 Tm

T_{rev} = 1.9155 µs $\qquad U_{\Sigma}$ = 626.5 MV

a. Single-turn mode:

I_{coast} = 31.3 mA $\qquad W_{beam}$ = 37.5 J

$\varepsilon_{x,y}$ = 2.0 mm mrad

$(\Delta p/p)_o = 2.8 \cdot 10^{-5}$ (coasting beam)

b. Multi-turn mode:

I_{coast} = 610 mA $\qquad W_{beam}$ = 733 J

ε_x = 58 mm mrad $\qquad \varepsilon_y$ = 19.4 mm mrad

$(\Delta p/p)_o = 1.55 \cdot 10^{-4}$

2.2. Acceleration to the maximum possible energy

The advantage of this procedure is:

Shorter bunches, lower emittances, higher heating power density than in the lower-energy case *without* cooling, in spite of a longer range,

Higher than the favourite energy range of 50 MeV/u increases the production of radionuclides somewhat, though still not dramatic. We should also consider that final focusing at 18 Tm would require a new fine-focus lens, probably superconducting or pulsed.

Parameters:

BR = 18 Tm $\qquad \beta\gamma$ = 0.6816

E_k/A = 195.8 MeV/u $\qquad U_{\Sigma}$ = 1.66 GV

	lower ion energy cooled beam		higher ion energy uncooled beam	
Injection mode→	single-turn	multi-turn	single-turn	multi-turn
γ	1.0791		1.2102	
U_{Σ}	626.5 MV		1660 MV	
Q	0.06 µAs	1.17 µAs	0.06 µAs	1.17 µAs.
F_b	0.15	0.2	0.2	0.3
$(\Delta p/p)_o$	$8.7 \cdot 10^{-4}$	$2 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	$6 \cdot 10^{-4}$
$\hat{U}_{th}$	9.2 kV	29 kV	2.2 kV	2.4 kV
Σ_o	0.037	0.10	0.06	0.30
$\hat{U}$	9.6 kV	32 kV	2.3 kV	3.1 kV
f	0.522 MHz	0.522 MHz	0.783 MHz	0.783 MHz

Table I

5, Fast Bunching

5.1. Voltage Requirements

The tolerable momentum spread is smaller for beams with smaller emittance. Therefore, we assume only 0.7% for the small emittance case. This limits the allowed compression factor.

	lower ion energy cooled beam,		higher ion energy uncooled beam	
Injection mode→	single-turn	multi-turn	single-turn	multi-turn
h	3	3	2	2
F_b (on this harm.)	0.45	0.6	0.4	0.6
f_c, compression	8	5	18	15
τ_{eff} after compr.	35.9 ns	76.6 ns	14.2 ns	25.5 ns
$\Delta p/p$ after compr.	0.7%	1%	0.7%	1%
$\hat{U}$ (1.566 MHz)	200 kV	310 kV	360 kV	290 kV
No. of turns for beam rotation	203	118	604	589

Table II

Injection mode→	lower ion energy cooled beam, single-turn	lower ion energy cooled beam, multi-turn	higher ion energy uncooled beam, single-turn	higher ion energy uncooled beam, multi-turn
Range (cold solid)	0.46 g/cm^2	0.46 g/cm^2	1.72 g/cm^2	1.72 g/cm^2
ε	1.4 mm mrad	7 mm mrad	2 mm mrad	34 mm mrad
r_{foc}	0.1635 mm	0.41 mm	0.2 mm	1.0 mm
m_{target}	0.38 mg	2.4 mg	2.2 mg	54 mg
W_{beam}	37.5 J	733 J	99.6 J	1942 J
w_{target}	100 kJ/g	305 kJ/g	45 kJ/g	36 kJ/g
τ_{eff}	35.9 ns	76.6 ns	14.2 ns	25.5 ns
P_{beam}	1.04 GW	9.6 GW	7.0 GW	76 GW
p_{target}	2.7 TW/g	4.0 TW/g	3.1 TW/g	1.4 TW/g
kT_{target}	10 eV	12 eV	11 eV	7 eV

Table III

Appendix

Collection of formulae used in this paper

2a. Incohärente Raumladungsgrenze

"Ring-Kapazität"

$$C_R = 174.8\ \mathrm{pF}\,\frac{\Delta\nu}{0.25}\,\frac{\varepsilon_v}{\mathrm{m}}\,(1+\sqrt{\varepsilon_h/\varepsilon_v})\,F_b\,g$$

$\Delta\nu$ = incoh. Tune-Shift; ε_h = hor. Emittanz; ε_v = vert. Emittanz (nicht Phasenfläche!);
Beachten: 1 mm mrad = 1 µm

F_b = Bunch.-Faktor = $I_{coast}/I_{max.}$, wenn alle Buckets gefüllt werden.

g = Formfaktor = $\frac{1}{2}+2\ln\frac{a_{tube}}{a}$; a_{tube} = Rohrradius, a = Strahlradius

RL-Grenze (max. Ladung)

$U_\Sigma = \frac{E_k}{qe}$ (= U_{Linac} bei Injektion durch einen Linac) (siehe auch Seite 1)

$$Q_{max} = C_R\,U_\Sigma\,\frac{\gamma(\gamma+1)}{2} \quad \text{"relativist. Bonus"}$$

$$= qeN_{max}$$

2b. Keil-Schnell-Grenze (Entdämpfung von Strahl-Schallwellen auf dem "Coasting Beam) (Formel nach Laclare/Kalisch)

$$I_{KS} = \frac{\left(\frac{\delta p}{p}\right)^2_{fwhm}\frac{mc^2}{qe}\beta^2\gamma\eta}{\frac{Z_n}{n}F} \approx \frac{2\left(\frac{\Delta p}{p}\right)^2_{hwbas}U_\Sigma(1+\gamma)}{\frac{Z_n}{n}F\,\gamma^3}$$

(schwach relativistische Näherung, $\eta \approx 1/\gamma^2$)

$\eta = \frac{p}{\omega}\frac{\partial\omega}{\partial p}$; F = Verteilungs-Formfaktor; Z_n = Strahlimpedanz der $n$ten Harmonischen

Faustregel: $\frac{Z_n}{n} \approx \frac{188\,\Omega}{\beta\gamma^2}g$

$$\rightarrow \quad I_{KS} \approx \left(\frac{\Delta p}{p}\right)^2_{hwbas}\frac{U_\Sigma\,\beta(1+\gamma)}{94\,\Omega g F\gamma}$$

Der Strahlstrom (coasting oder gebuncht) kann je nach Phasenraum-Verteilung um den Faktor F_{KS} überschritten werden. Der zulässige Faktor F_{KS} kann experimentell ermittelt werden. Eine Abschätzung der Situation erlaubt der Raumladungsparameter Σ_O.

$$F_{KS} = \frac{\hat I}{I_{KS}} = \frac{\Sigma_O}{(\Sigma_O)_{KS}} \quad \text{"Keil-Schnell-Faktor"}$$

$\hat I$ = Strahlstrom in Bunchmitte = $\frac{\beta c Q h}{2\pi R F_b}$; Q = Ladung pro Bunch

$(\Sigma_O)_{KS} \approx \frac{2}{\pi F} \approx 1$ Σ_O siehe nächste Seite

Bucketspannung zum Bunchdrehen:

$$\hat{U} = \frac{(\Delta p/p)_1^2}{\Delta\varphi_2^2} \frac{2\pi h\,\eta\, mc^2\beta^2\gamma}{qe}(1+\Sigma_1) \qquad \Sigma_1 = \frac{2\,\Delta\varphi_2}{\Delta\varphi_1+\Delta\varphi_2}\Sigma_0$$

$$\frac{(\Delta p/p)_1}{\Delta\varphi_2} = \frac{(\Delta p/p)_2}{\Delta\varphi_1}$$

Synchrotron-Phase-Advance *pro Umlauf* während Bunchrotation (Näherungsformel):

$$\sigma_{s0} \approx 2\pi h\eta \frac{(\Delta p/p)_1}{\Delta\varphi_2}\frac{1}{\sqrt{1+\Sigma_1}}$$ (mit RL.: zunächst größer, dann kleiner.)

Zahl der Umläufe zum Bunchdrehen (Näherung)

$$N_{1/4} \approx \frac{\Delta\varphi_2}{4h\eta(\Delta p/p)_1}\sqrt{1+\Sigma_1}$$

4. Elektronen-Kühlen und Intrabeam-Streuung

a. Kühl-Gleichgewicht (nach T. Winkler)

$$\left(\frac{\Delta p}{p}\right)_{equil} \approx f_{nonid}\sqrt{\frac{\varepsilon_{equil}}{\beta_{av}}} \approx C_{cooler}\left(N\frac{q^4}{A^2}\right)^{0.27}$$

(Simonsson (NIM **A284** (1989),264-7) erhielt aus Computer-Simulationen mit CRYRING-Daten einen Exponenten von 0.212).

β_{av} = mittlere transversale β-Funktion ≈ 20 m für ESR

ESR, Elektronenstrom 250 mA:

Nicht-Idealitäts-Faktor (Fehljustage, Ein- und Auslenkung des e^--Strahls); Mittelwert für beide Richtungen:

$$f_{nonid} = 0.5$$
$$C_{cooler} \approx 0.13\cdot 10^{-6}$$

Nach Simonsson besteht eine berechnete $\beta\gamma$-Abhängigkeit von $C_{cooler} \sim (\beta\gamma)^{-0.598}$. Der Elektronenstrom geht nach Winkler in $C_{cooler} \sim (I_{electrons})^{-0.3}$ ein, allerdings wird auch f_{nonid} beeinflußt.

b. Intrabeam-Scattering (s. z. B. J. Struckmeier, Part. Acc. **45** (1994), 229-52)

Innerer Reibungs-Koeffizient oder Reibungs-Rate

$$\tau_f^{-1} = \frac{16\sqrt{\pi}}{3}\, n\, c\, \frac{q^4}{A^2} r_n^2 \prod_{xyz}\sqrt{\frac{mc^2}{2kT}}\,\log\Lambda$$
$$= \sqrt{\frac{8}{\pi}}\,\frac{I}{qe}\,\frac{q^4}{A^2}\,\frac{r_n^2}{\beta^4\varepsilon_x\varepsilon_y(\Delta p/p)_0}\,\log\Lambda$$