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H^0 STARK STRIPPING AND COMPONENT IRRADIATION IN FERMILAB BOOSTER*

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Abstract

In foil stripping of H^- some fraction of the emerging neutral H^0 will be in excited states, which can then strip through the Stark effect in the magnetic field of the downstream orbit bump magnet. The resultant H^+ will experience a depleted net kick compared to protons emerging from the foil and will track on trajectories different from the nominal circulating beam. This will lead to irradiation of downstream machine components. An analysis of these processes is of particular importance looking forward to the much higher beam power of the Fermilab PIP-II era. This study investigates where these errant protons will be lost, how much power is deposited, and whether this will be a shielding concern.

INTRODUCTION

The Fermilab Booster is a 474 m circumference synchrotron constructed from 24 repetitive cells, each of which comprises two each of focusing (F) and defocusing (D) 2.889 m gradient magnets plus a 6 m long (L) and a 1.2 m short (S) straight section. Cells have lattice structure of the form F.D_L_D.F_S.

H^- ions extracted from the linac are injected into Booster on a trajectory parallel to the closed orbit. The injection scheme passes beams through an orbit 4-bump of pulsed dipole magnets ('ORBUMP's). Both the injected H^- and circulating H^+ beams pass through the two upstream ORBUMP magnets. These magnets bend the circulating H^+ beam upwards and the injected H^- beam downwards so that they overlap. Both the H^- and H^+ pass through a thin carbon stripping file located between the 2nd and 3rd ORBUMPs, which removes the electrons from most of the H^- to yield protons. The downstream ORBUMP magnets bend the protons onto the closed orbit.

This loading scheme that overlays injected beam with circulating beam allows increases in Booster beam intensity but is subject to particle losses from several sources. These include large angle scattering from multiple interactions within the stripping foil and losses from Stark stripping of residual neutrals in the ORBUMP magnet immediately downstream of the foil. Stark stripping is the subject of the current study.

Currently, with 400 MeV H^- injection the incident beam power is 4.3 kW and power deposited from Stark stripping is not an issue. In the upgrade era of PIP-II, however, the increase to 800 MeV, coupled with higher bunch intensities and repetition rate, will quadruple incident beam power to 17.2 kW and energy deposition needs to be re-evaluated.

There are five steps in this study. It is necessary to determine the following:

- The fraction of H^- that convert to H^0 in the foil;
- The H^0 excited states of principle quantum number n (denoted h_n^0) that are a concern for stripping within ORBUMP3;
- The fractional populations of these h_n^0 states;
- The stripping distribution of each h_n^0 state within ORBUMP3, and;
- Track the H^+ from Stark stripping of the h_n^0 to determine power distributed on downstream elements.

H^0 STARK STRIPPING MODEL

Total H^0 production and yields of states h_n^0 can be determined from the excellent study of Gulley *et al.* [1]. The relevant sub-set of results are summarized in Fig. 1.

ρ (μg/cm²)	H^0 total (10^{-5})	h_4^0 (10^{-5})	h_5^0 (10^{-5})	h_6^0 (10^{-5})
550	115.36	3.6648	2.5699	2.7317
600	59.63	1.8815	1.3550	1.6044
650	30.82	0.9615	0.7059	0.9366

Figure 1: H^0 species yields at 800 MeV as functions of carbon foil thickness, normalized to unit H^- intensity.

In the present study the foil thickness ρ = 600 μg/cm² is chosen, which is a reasonable compromise to offset the conflicting goals of minimizing large angle scattering in the foil and minimizing neutral production (99.940% H^- stripping efficiency).

In a magnetic field the Stark effect splits each principal state into n(n+1)/2 sub-states. The lifetimes τ of the n=4 to 6 sub-states as functions of magnetic field B are illustrated in Fig. 2. It is remarkable that τ varies by several orders of magnitude across relatively small variations in B. Preliminary considerations of ORBUMP design for PIP-II produce a peak field of 0.3734 T, as indicated.

It can be generally concluded that n=5 and 6 will strip almost immediately, more tightly bound states $n \leq 3$ (not shown) won't Stark strip, while n=4 sub-states require special consideration.

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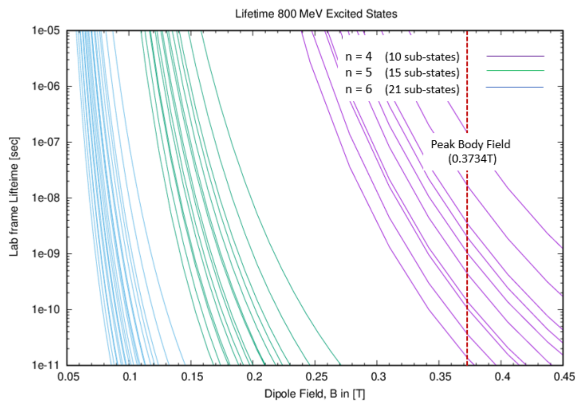

Figure 2: Lifetimes of h_n^0 sub-states for n=4, 5 and 6 as functions of magnetic field at 800 MeV [2].

An 'ideal' magnet (*i.e.*: a step-function end-field) would be 886 mm of 0.3734 T field. The ORBUMP magnets will not be ideal, of course, and preliminary Opera modelling of a candidate design [3] produces the end-field distribution shown in Fig. 3.

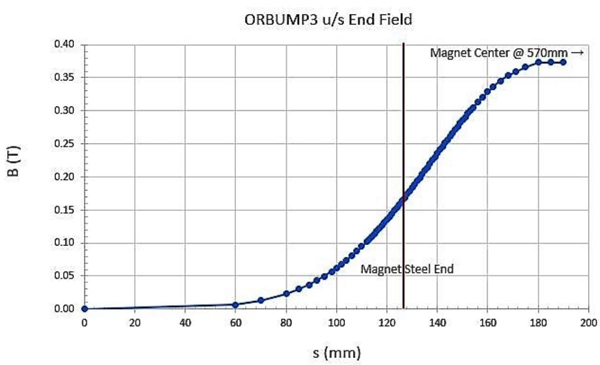

Figure 3: ORBUMP end-field distribution from an Opera calculation [3].

The upstream end of an ideal magnet would occur at 127 mm on the scale shown, with the magnet center at 570 mm. The end-field distribution of the Opera magnet extends from 0 to 180 mm or 53 mm into the body of the physical magnet.

Combining the results from Fig. 2, that show the dependence of τ on *B* field, with the magnetic distribution in Fig. 4, it is possible to define a localized lifetime as a function of distance z into the magnet.

The resulting τ(z) are highly non-linear functions of z but the depletion of h_n^0 and corresponding growth of H^+ are characterized by the equations:

$$\frac{dh_n^0}{dz} = -\frac{1}{\tau(z)\cdot\beta c}\cdot h_n^0 \qquad (1)$$
$$\frac{dH^+}{dz} = +\frac{1}{\tau(z)\cdot\beta c}\cdot h_n^0$$

which have general solutions:

$$h_n^0(z) = e^{-\int_0^z dz'/\tau(z')\cdot\beta c} \qquad (2)$$
$$H^+(z) = (1 - e^{-\int_0^z dz'/\tau(z')\cdot\beta c})$$

For τ(z) → τ = constant these equations simplify to the general analytic form that, for example, describes charge-changing stripping of H^- in a foil.

The solutions to these equations for h_n^0 and H^+ evolutions are discussed in the subsequent section.

STRIPPING CALCULATIONS

$$n = 6:\ h_6^0 \rightarrow H^+$$

The excited n=6 H^0 states are unimportant from the viewpoint of energy deposition. All 21 sub-states strip almost immediately in the upstream end of the end-field, between 0.087 → 0.144 T. This corresponds to a depletion in the 67.74 mr nominal kick of only 0.36 → 0.69 mr. Consequently, apart from a very small fraction, the H^+ do not irradiate downstream elements – the vast majority of H^+ enter the circulating beam.

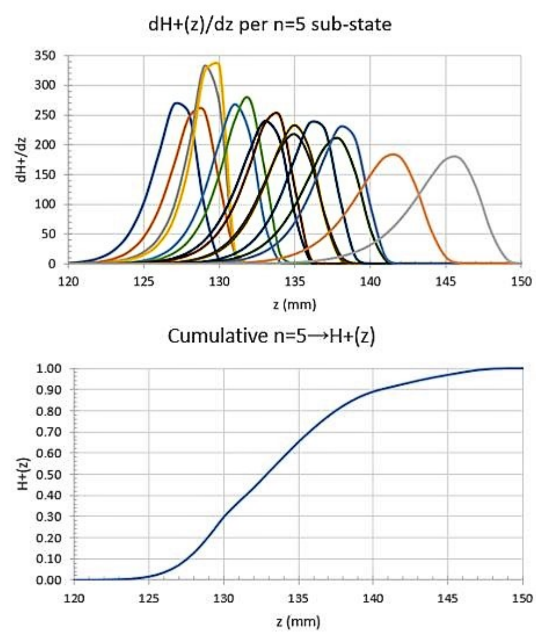

Figure 4: H^+ production as functions of location z in kicker orbump3 from Stark stripping of the 15 h_5^0 sub-states.

$$n = 5:\ h_5^0 \rightarrow H^+$$

H^+ production curves are shown in Fig. 4. Stripping of the 15 h_5^0 sub-states is strongly peaked in the end-field over a 30 mm range, from 120 → 150 mm, or 0.136 → 0.290 T (peak field of 0.3734 T occurs at 180 mm). The cumulative H^+ production curve shows that 100% of the h_5^0 strip.

$$n = 4:\ h_4^0 \rightarrow H^+$$

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H^+ production curves are shown in Fig. 5. Stripping of the 10 h_4^0 sub-states is strongly peaked in the transition region from the end-field to peak body field. The cumulative H^+ production curve shows that 75% of the h_4^0 strip. That 25% of the h_4^0 survive as neutrals is a reflection of the relatively long lifetimes of these states even in the peak body field (Fig. 2).

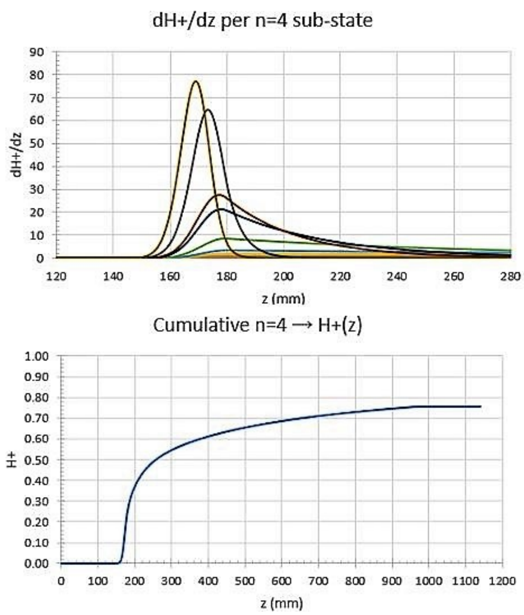

Figure 5: H^+ production as functions of location z in kicker orbump3 from Stark stripping of the 10 h_4^0 sub-states.

DEPOSITED POWER

The accelerator program MAD-X [4] was used to track the H^+ from Stark stripping. MAD-X does not track neutrals, nor is it equipped to include H^0 stripping interactions so some innovation was called for. The following steps were taken to accurately model H^+ trajectories:

- The 3rd ORBUMP magnetic field was sliced into 1140 elements in 1 mm increments;
- From the cumulative H^+ production results Δz increments were determined in which the H^+ population grew in 5% steps. This identified magnet slices in which the mean field would strip an additional 5% of the h_n^0;
- *B* field was set to zero in all the upstream slices;
- The h_n^0 were then tracked as protons traveling through a drift up to the appropriate slice where the h_n^0 would strip and then track as H^+ onwards seeing the full downstream magnetic field.

10^6 particles were tracked for each of n=4, 5 and 6 from the foil in L11 through to L20 and losses recorded. Those losses are reported in Fig. 6. Also included is the total power deposited on those elements.

# sub-states	n=4 (10) 75.28% strip	n=5 (15) 100% strip	n=6 (21) 100% strip	Total Power Deposited (mW)
CORRL11	22.672 ± 0.055			73.37 ± 0.17
DMAGD11	45.353 ± 0.078	0.002 ± 0.001		146.81 ± 0.24
FMAGD11	7.208 ± 0.031	4.514 ± 0.021		33.85 ±0.11
DMAGU12	0.050 ± 0.002	1.034 ± 0.010	0.064 ± 0.003	2.75 ±0.03
NOTCHER (1st)		2.814 ± 0.017	0.152 ± 0.004	6.98 ±0.04
DMAGD12		3.406 ± 0.019	1.452 ± 0.012	11.94 ±0.06
FMAGD15		1.346 ± 0.012	0.424 ± 0.006	7.20 ±0.03
DMAGD17		3.776 ± 0.019	1.471 ± 0.012	12.86 ±0.06
FMAGD17		0.385 ± 0.006	0.200 ± 0.004	1.45 ±0.02
Total % Lost	75.28 ± 0.10	17.28 ± 0.04	3.76 ± 0.02	

Figure 6: Fractional losses of the h_n^0 on downstream elements and total power deposited from a 17.2 kW H^- beam.

- The loss distribution reveals more tightly bound states strip further into ORBUMP, leading to greater kick depletion and losses moving upstream;
- Losses occur almost entirely on the main dipoles;
- Only the corrector package at L11 and first of the 6 notcher kickers in L12 received losses – no losses were recorded on other correctors or RF cavities;
- The 73 and 7 mW deposited on vulnerable components are negligible.

DISCUSSION

The analysis presented here concluded that irradiation of sensitive elements from H^0 Stark stripping in Fermilab Booster will not be a component-activation issue in the PIP-II era. Nonetheless, the techniques developed here are directly applicable to studies of the impact on losses from, for example, peak magnetic field and end-field distribution, thus making this approach a valuable tool in magnet design.

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