INJECTION DESIGN FOR FERMILAB PROJECT X*

D.E. Johnson#, C.Y. Tan, Z. Tang Fermi National Accelerator Laboratory, Batavia, IL, 60510 USA

Abstract

Fermilab is proposing a staged approach for Project X, a high power proton accelerator system. The first stage of this project will be to construct a 1 GeV continuous wave (CW) H^- superconducting linear accelerator to inject into the existing 8 GeV Booster synchrotron ultimately providing in excess of 1 MW beam power for the Neutrino program out of the Main Injector. We will discuss the current project plans for injection into the Booster and related issues.

INTRODUCTION

Fermilab accelerator upgrade project called Project X has investigated several different accelerator configurations [1,2] since the initial Proton Driver [3,4] was proposed in 2000. The current base line design configuration [5] consists of a 3 GeV superconducting CW H^- linac providing beam simultaneous to a 3 GeV Experimental Program [6] and a 3-8 GeV pulsed superconducting linac for multi-turn H- injection into the Recycler Ring at 8 GeV. The issues relating to 8 GeV multi-turn injection into the Recycler were discussed at HB2010 [7].

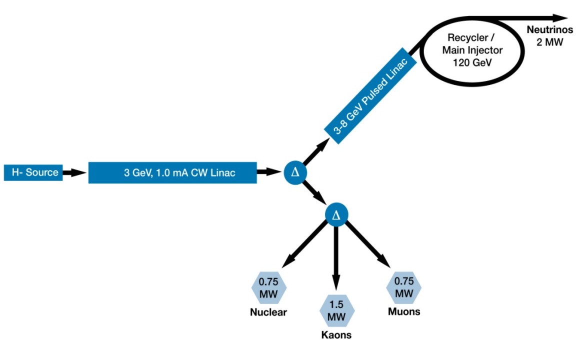

Figure 1: Block diagram of the accelerator configuration in the Project-X reference design.

Although the reference design is still the base line, financial and budgetary constraints led the project to investigate a staged approach which will utilize some of the existing infrastructure [8].

STAGED APPROACH

The functionality of the reference design can be realized by a set of three stages each capable of increasing the beam power to the long base line neutrino program while supporting a robust experimental program at the 1, 3, and 8 GeV energy ranges. More information about the staging may be found in reference 8. A block diagram of a staged approach is shown in Figure 2 with each of the stages color coded: existing rings in black, stage 1 in blue, 2 in green, and 3 in red. Not shown is the existing 400 MeV linac feeding the Booster. Here, we will concentrate only on Stage 1.

Stage 1

The first stage replaces the existing 400 MeV pulsed Linac with a 1 GeV superconducting CW Linac with an average current of 1 mA. About 2% of the linac beam will be injected into an upgraded 15 Hz Booster accelerator leading to a 50% increase the per pulse proton intensity delivered from the Booster to the Main Injector, thus establishing the potential of delivering up to 1.2MW beam power to the long baseline neutrino experiments. The balance of the linac beam can be delivered to the newly developed Muon campus, providing a factor of ten increase in beam power available to the Mu2e experiment and/or to newly developing programs devoted to nuclear electric dipole moments (edm), ultra-cold neutrons, and possible energy applications [8].

The integration of the new linac into the complex requires the upgrade of the Booster injection system from 400 MeV to 1 GeV, new transport lines, and potentially new civil construction, depending on siting choices.

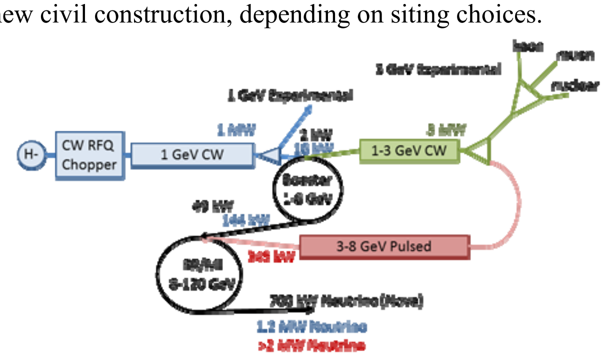

Figure 2: A staged approach for Project X.

CURRENT BOOSTER CONFIGURATION

The current injections into Booster utilizes a linac pulse length equivalent to 1-10 turns @~2.2 us/turn and does not utilize any transverse phase space painting. The transport line from the linac is "matched to the ring lattice and therefore the linac transverse emittance defines the "base" emittance of the beam in the Booster. Adiabatic capture is utilized. Typical injection intensities are around 5E12 ions/cycle at a 7.5 Hz injection repetition rate corresponding to an injected beam power of 2.4 kW. For the typical carbon foil thickness of ~380 $\mu g/cm^2$, the expected stripping efficiency is 99.9% leaving only 0.1%

*Work supported by US DOE under contract #DE-AC02-07CH11359
#dej@fnal.gov

ISBN 978-3-95450-118-2

Copyright (C) 2012 by the respective authors — CC BY 3.0

of the beam exiting the foil as H^0. Two loss points corresponding to the H^0 and H^- missing the foil (or un-stripped) have been identified on the aisle side of the second gradient magnet downstream of the injection chicane. Radiation survey of these locations, upon turning the Booster off, show residual radiation levels on the order of a few R "on contact" [9]. These loss points will need to be addressed in any new design which translates to the incorporation of a shielded injection absorber.

Booster Lattice

The Booster has 24 periods of an oFDooDFo structure made up of gradient magnets. One of the 6m long straight section between the defocusing gradient magnets is utilized for injection. The lattice functions of the injection straight section are shown in Figure 3. A three dipole pulsed chicane is used to merge the incoming H^- with the circulating protons. A carbon foil changing system (with 8 foil holders) is located just after the center (or merging) dipole. The chicane displaces the closed orbit by about 45 mm at the foil location. The required angle for the first and last dipoles, θ, is roughly 22 mr with the center dipole being twice that of the first/last. The incoming H- trajectory is 3θ, 66 mr, with respect to the straight section center line (enough to clear the upstream gradient magnet). The current injection chicane layout is shown in Figure 4.

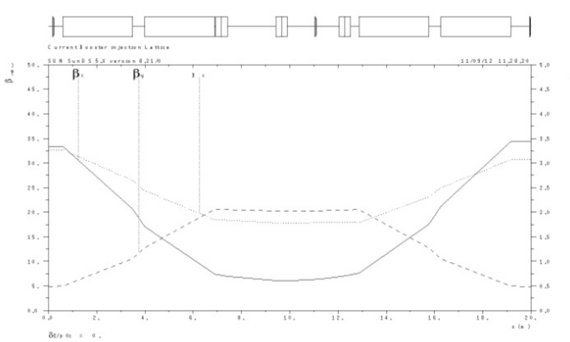

Figure 3: Booster Injection Lattice.

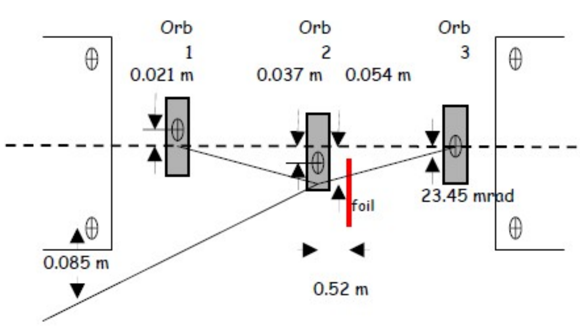

Figure 4: Current Booster injection chicane layout [10].

1 GEV BOOSTER INJECTION

To meet the proton intensity requirement out of the Recycler/Main Injector of 7.5E13 protons/cycle with a 95% slip stacking/acceleration efficiency, the Booster must provide 7.8E13 in 12 pulses of 6.5E12/15 Hz cycle. If we assume a 90 to 95% injection/acceleration efficiency in the Booster, the linac must provide 7 to 7.3E12/15 Hz Booster cycle. If beam is run on all cycles this corresponds to approximately 18 kW injected beam power and 125 kW extracted at 8 GeV.

Linac Parameters

The CW 2.1 MeV RFQ creates a bunch train of 162.5 MHz bunches. A bunch-by-bunch chopper, located in the MEBT, can create the required bunch train to match into the Booster RF structure. The average linac current is 1 mA over a microsecond creating a bunch intensity of 3.8E7 H- ions/bunch. The high energy end of the linac utilizes 650 MHz superconducting elliptical cavities. The rms longitudinal emittance is approximately 9.0E-5 eV-sec with a bunch length of 3.8 ps and δE/E of 0.025%. The transverse horizontal and vertical rms emittances are 0.25 and 0.3 mm-mr, respectively.

Booster Injection Energy Options

In order to accumulate the 7.3E12 for a single injection, a linac bunch train of 1.92E5 bunches is required, assuming all linac bunches are filled uniformly. The revolution period of 1 GeV protons in the Booster is approx. 1.8 µs which means 295 linac bunches occupy a single turn in the Booster and 650 turns for injection would be required. The injection time would then be approximately 1.17 ms, almost a factor of 50 increase in injection time.

The Booster is made up of 48 resonant RLC cells connected in series. These are powered by four 12 phase power supplies with a sinusoidal waveform. Typically, injection would take place at the minimum field, BMIN, of this resonant circuit. Since the injection time for the low current linac is long compared to the 15Hz energy ramp (1.17 ms vs 24 µs as in present operation) two options exist for injection at this higher energy: 1) create an injection front porch by modifying the main magnet power supply system (or some other method) thus injecting at a fix energy and 2) start injection before BMIN and follow the Booster field thru BMIN and up the start of the ramp requiring both the Booster RF and linac track the changing momentum through the injection process. A third option, that will not be discussed here, is to install a permanent magnet accumulator ring in the already crowded Booster tunnel, to be used to accumulate charge and use single turn synchronous transfer to the Booster [11]. This option would then provide an additional flexibility to reformat the CW linac beam for matching to experimental needs.

A preliminary simulation involving a single Booster resonant cell (i.e. two gradient magnets) has been completed [12]. This showed that the sinusoidal

Copyright (C) 2012 by the respective authors — CC BY 3.0

ISBN 978-3-95450-118-2

waveform at injection energy may be modified to create a "constant current" injection porch with a length of approximately 1 ms. Additional simulations are required to create a model of the entire ring to determine the required power supply modifications and verify voltage to ground and harmonic issues will not be a problem. Although this first option may require significant power supply modifications, it would allow the injection to take place at a constant energy and allow micro-bunch transfers into a stationary bucket at an energy offset of about 4 MeV.

The second option is to inject on the ramp which means that injection would start about 500 µs before and end500 µs after the minimum. This corresponds to 4 MeV energy offset and a dp/p offset of 0.26%. Although the linac is capable of following the required energy swing [13], this concept needs to be further developed.

Currently, the Booster RF frequency is a harmonic h=84 of the revolution frequency. The Main Injector circumference is 7 times that of the Booster with a harmonic number of 588. At 1 GeV and h=84 the Booster RF frequency, f_{RF} = 46.4635 MHz. The ratio of the bunch spacing to f_{RF} is 3.4974. Figure 5 shows the injected 162.5 MHz bunch pattern spacing superimposed over the Booster RF phase. The positive zero crossing of the red curve represents the center of the Booster RF bucket. The blue impulses represent the injected bunch pattern with the negative impulses being chopped out of the bunch train leaving only those bunches that would land in the stable region of the Booster bucket. The harmonic ratio of ~3.5 is clearly seen.

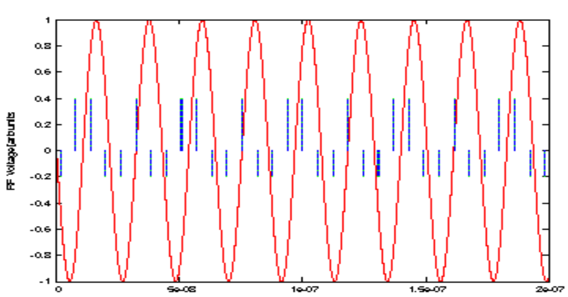

Figure 5: Phase of injected bunches with respect to Booster RF. Negative bunches will be chopped out and will not be injected.

Given this bunch pattern, 1) alternate buckets are filled with either one or two bunches each turn, 2) the peak linac bunch current must be increased or the injection time must be increased, 3) there must be a programmed phase which slews the Booster RF phase on a turn by turn basis for longitudinal painting, 4)the harmonic number, h, of the Booster and hence the Recycler/Main Injector ($h_{RR/MI} = 7*h_{Booster}$) must change from an even to odd integer such that each bucket will be evenly filled at the end of injection, thus requiring two turns to fill each bucket with three bunches. For a 600 turn injection, this filling pattern will require the peak linac bunch intensity to increase by a factor of about 2.5.

Preliminary results for macro-bunch injection into a Booster stationary bucket are shown in Figure 6. Here, it is assumed that the micro-bunches from linac have a longitudinal emittance of 2E-5 eV-sec. In this simulation, the micro-bunches were randomly injected within three different phase limits, φ_{MAX}, of ±180°, ±90°, and ±60° and accumulated for 1 ms then ramped. In addition, two different harmonics were added to the fundamental in a specific ratio (i.e. ~V_{RF}/h, where h is either 2 or 3 and V_{RF} is the fundamental voltage). The fundamental RF voltage used in the simulations was 1 MV. The survivability of each condition was tabulated. It is clear from the data that the smallest phase range had the best transmission. Clearly, the addition of the 2nd harmonic reduces the momentum spread of the accumulated bunch in the Booster. Given that the measured full momentum acceptance of the Booster [14] is 0.4% (i.e. ±0.15-0.2%), caution must be exercised not to exceed this in filling the new Booster bucket. It is clear that the addition of the second harmonic results in a smallest momentum spread as well as limiting the phase range at which the bucket is filled. The range of phases in which to inject is governed by the micro-bunch spacing of the injected linac beam. The phase over which the linac bunches may be painted is approximately given by $\varphi_{MAX} - f_{RF}/2f_{bunch}*360$. Further simulations are required.

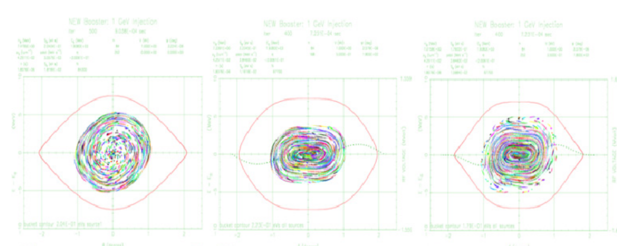

Figure 6: Results of ESME simulations for three RF harmonics with limiting bunch injection to +/- 90° within the Booster RF bucket. From left to right fundamental only, fundamental plus 2nd harmonic, and fundamental plus 3rd harmonic.

Booster Geometry

The 1 GeV injection straight section at SNS in 12.5 m between quadrupoles and utilizes a 4 dipole chicane with an injection septum. A secondary foil is utilized to convert any neutrals or H- that miss the foil into protons and transport them to an external absorber. It should be noted that the injected beam power at SNS is on the order of 50-60 times that expected here. The straight section in the Booster is only 6 m between gradient magnets and does not contain an injection absorber. To create additional room for and injection absorber, the defocusing gradient magnets are shortened by 25% keeping the bend center fixed. This modification introduces an rms variation in the lattice and dispersion functions on the order 4% which may be corrected by reducing the focusing of the modified magnets to roughly 98% of the

ISBN 978-3-95450-118-2

Copyright (C) 2012 by the respective authors — CC BY 3.0

scaled value [15]. This modification increased the straight section length by 12% and will allow the space for an injection absorber.

Two potential geometries are considered for the injection chicane, a three magnet chicane (as in current Booster configuration) and a four magnet chicane (previously used in the Booster before 2005 and utilized at other facilities as SNS and JPARC). Figure 6 shows the 6σ beam envelope of a 1 GeV 20 π circulating beam for a three magnet chicane. Here the adjacent D gradient magnets are shortened and the length of the chicane is shortened to make room for an absorber downstream of the third chicane dipole. The stripping foil, still located after the middle dipole but farther upstream than the present 400 MeV location such that the H^0 and H^- trajectories cross the centerline and may be captured in an absorber before entering the downstream gradient magnet. The up and downstream dipoles run at an angle of approx 25 mr with the center dipole at about 50 mr. The H- injection trajectory is 75 mr wrt the Booster centerline. The face of the absorber would be 0.95m downstream of the last chicane dipole with the inside edge at about 2.0 cm from the centerline to intercept both the H^0 and H^- before they enter the downstream gradient magnet.

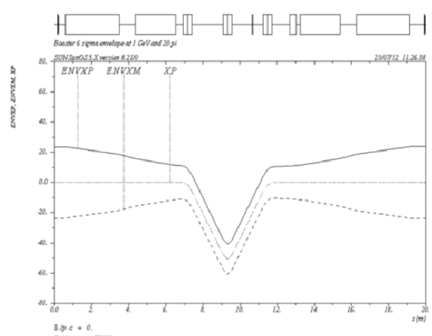

Figure 7: Beam envelope for a revised 3 dipole horizontal chicane.

The other potential orientation is to utilize a 4 dipole chicane. The incoming H- trajectory must miss the upstream gradient magnet and chicane dipole. A septum magnet to bring the H- into the merging magnet (2nd chicane dipole) is required with a bend angle of approximately 78 mr enough to miss the vertical size of the upstream gradient magnet. The bend angles for the chicane dipoles are in the 20-25 mr range, well within the capability of the existing chicane dipoles. The waste beam would emerge from the foil at a trajectory 60 mm above the vertical mid-plane to impact the absorber.

Both of these configurations should further developed and used in transverse painting simulations.

Transverse Painting

There are two main options for performing transverse phase space painting into the Booster, painting in both dimensions in the ring and painting in one dimension in the ring and steering from the beam line in the other

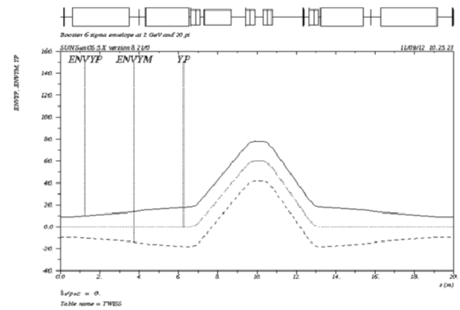

Figure 8: Beam envelope for a vertical 4 bump chicane.

dimension. Both of these techniques are utilized in existing machines: SNS paints in both dimensions and JPARC paints and steers. In each of these scenarios the painting algorithms may be either correlated or anti-correlated in direction of painting of small to large or large to small amplitude. In addition, the functional form needs to be optimized to minimize over painting of the phase space as well as producing a KV-like distribution and minimizing the number of parasitic interactions between the circulating protons and the foil.

Injection Foil Issues

The expected injected beam power for Stage 1 will be a factor of 7.5 greater than the current beam power at 400 MeV. If we assume the same the stripping efficiency of 99.9% obtained at 400 MeV, then the foil thickness would be required to be 585 mg/cm^2 as scaled from Gulley [16]. The foil size and mounting geometry are determined by the injection chicane geometry, whether horizontal or vertical and three or four bump configuration. Other issues that will need to be addressed are the stripped electron trajectories as well as foil scattering of the injected and circulating beam.

As the final geometry has not been selected and the transverse painting simulations have not been performed to optimize the painting parameters, we cannot accurately predict peak foil temperatures. Since the injected intensity is relativity low (7.5E12/ms) and the injection time is reasonably long, the foil temperature will be dominated by the parasitic hits from the circulating protons. For a low intensity injected beam, the worst case foil temperature arises if there is no transverse painting, then the average number of hits each particle makes is $N_{turns}/2$. For a 1 ms injection with 625 injection turns the total foil hits, for the expected injection intensity 7E12/ms, is 2.35E15. We ignore energy deposition from the electrons or the energy taken away by delta rays. Each proton deposits 1.94 MeV-cm^2/g such that a total of 0.24 Joules is during each millisecond injection (or 240 watts) will be deposited in an area the size of the circulating beam. A thermal model for the time dependent heating of a carbon foil through ion energy deposition, including thermal conduction and radiation was implemented in ANSYS. The properties of the carbon foil are: thickness of 1.5 μm, density of 2.2 g/cm^3, thermal conductivity of 13.7 W/cm-K, emissivity of 0.8, and a temperature dependent value

Copyright (C) 2012 by the respective authors — CC BY 3.0

ISBN 978-3-95450-118-2

of specific heat of was constructed. For an elliptical beam with horizontal and vertical size of σ_x=3 mm and σ_y=6mm impinging on a foil of radius 5 cm [17] we see peak temperatures less that 1000 degrees, hence the foil heating does not appear to be an issue. Figure 9 shows the temperature distribution after the particles hit the foil (top) and the heating/cooling of the 15 Hz operation (bottom).

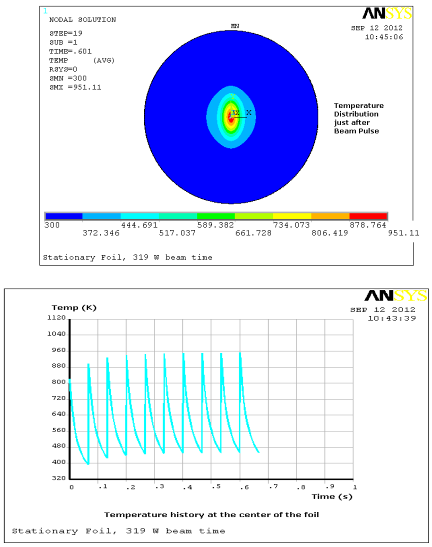

Figure 9: Preliminary estimate of foil heating for Booster 15 Hz injection.

Waste Beam

The waste beam that would get sent to the absorber is composed on H^- that miss the injection foil, H^- that are not stripped in passing through the foil, and H^0 (both in the ground and excited states) that emerge from the foil. If we assume 2% of the linac beam misses the foil and 0.1% emerges as H^0 then the absorber heat load will be determined primarily by the particles that miss the foil, about 350 watts. Most of the H^0 exiting the foil will typically be in the ground or lowest excited states (n<3) and will not strip. The lifetime of the Stark States of hydrogen are shown in Figure 10. Here, for the expected

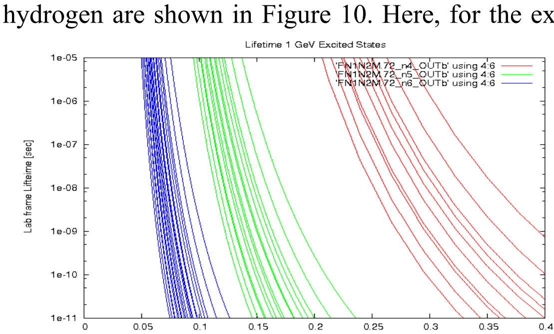

Figure: 10 Lifetime of 1 GeV Excited states in the presence of a magnetic field.

maximum chicane field of 0.3T only a few of the n=4 states are expected to strip before they reach the absorber. All higher states are stripped immediately and go into the circulating beam. The expected population in the n=4 state is a few 10^{-5}.

CONCLUSIONS

An initial look has been performed on the concept of injecting 1 GeV H^- from a low current CW superconducting linac into an upgraded Booster RCS. At this point the concept looks feasible, but many more simulations are needed.

ACKNOWLEDGMENT

The authors would like to thank the many staff from the Proton Source Dept., Dan Wolff, Jim Lackey, Milorad Popovic, Slava Yakovlev, and Meghan McAteer for many valuable conversations.

REFERENCES

[1] S. Holmes, "Staging Opportunities for Project X", ProjX docDB 1049, October 28, 2011.
[2] S. Holmes, "Project X: Status and Plans", ProjX docDB 953, seminar given at LBL and SLAC May 2011.
[3] W. Chou (ed), "The Proton Driver Study", Fermilab TM-2136, December 2000.
[4] G.W.Foster (ed), "Proton Driver Study II Part I", Fermilab TM-2169, May 2002.
[5] P. Derwent (ed), "Reference Design Report v1.0" ProjX docDB 776, November 2010.
[6] B. Tschirhart, "Project X and the Endless Frontier", ProjX docDB 1052, June 2012.
[7] D.E. Johnson, et al., "Project X: H- Injection design History and Challenges", proceedings of HB2010, Morschach, Switzerland, MOPD43, (2010).
[8] S. Holmes, "Project X Performance by Stage", ProjX docDB 1061-v7, June 2012.
[9] T. Sullivan, FNAL, private communication, August 2012.
[10] J. Lackey, et al., "Operation and Performance of the New Fermilab Booster H- Injection System, Fermilab-conf-07-248-AD, (2007).
[11] M. Popovic, et al. "A 1 GeV Accumulator Ring in the Booster Tunnel", ProjX docDB 1054-v1, May 2012.
[12] D. Wolff, FNAL, private communication, August 2012.
[13] V.P. Yakovlev, FNAL, private communication, July 2012.
[14] W. Chou, et al., "Fermilab Booster Modeling and Space Charge Study", proceedings PAC2003, p. 2925.
[15] M. McAteer, FNAL, private communication, July 2012.
[16] M.S. Gulley, et al., Physical review A53, 3201 (1996).
[17] Note: circular foil geometry from Rotating Foil project used in estimates and a more appropriate geometry will be used for actual painting simulations.

ISBN 978-3-95450-118-2

Copyright (C) 2012 by the respective authors — CC BY 3.0