# Reformatting Beams and Associated Issues


Valeri Lebedev

Fermilab


## Objectives

- Discussion of limitations on the Project X parameters coming from
  - Injection to Recycler
  - Injection to Accumulator ring
  - Bunch compression in Buncher ring


Fermilab Accelerator Advisory Committee

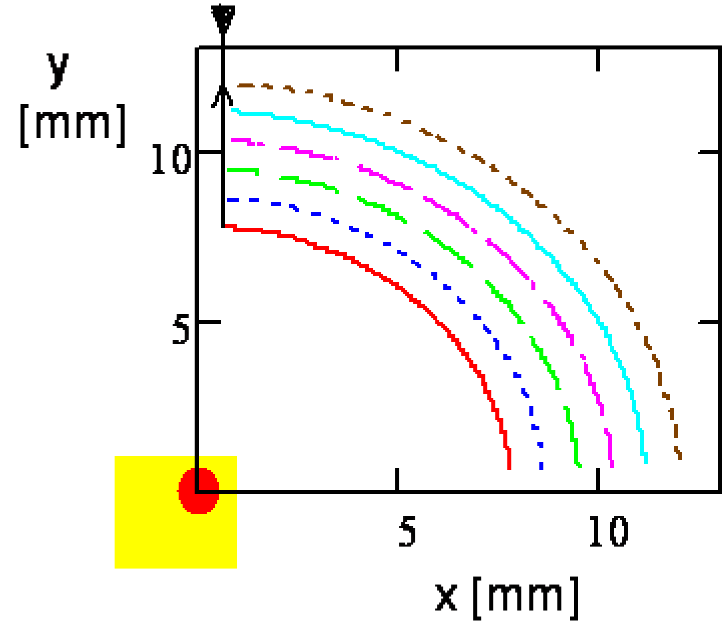
July 28-30, 2010

# Beam $H^-$ Strip-injection to Recycler

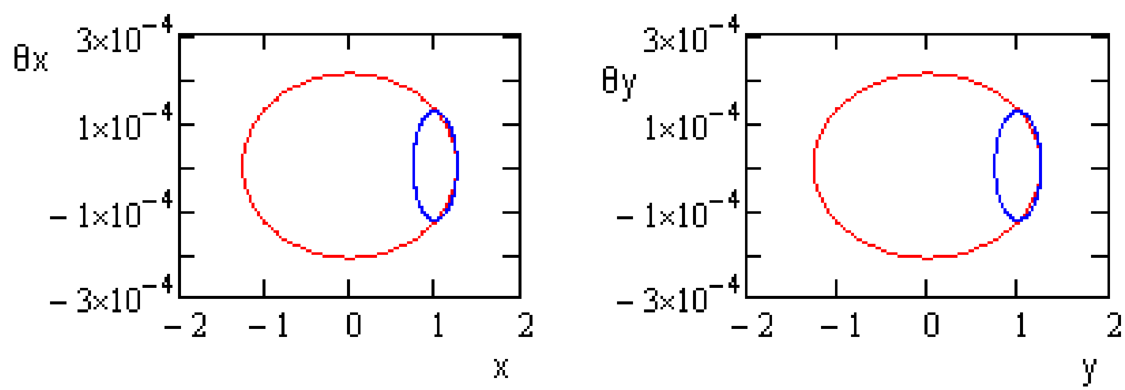
- Foil strip injection
  - Carbon foil
  - Liquid metal stream
- Laser strip injection

# Carbon foil strip injection to Recycler

- Foil will be destroyed at the first pulse for one pulse injection
- 6 pulses at 10 Hz give enough time for radiative cooling between pulses



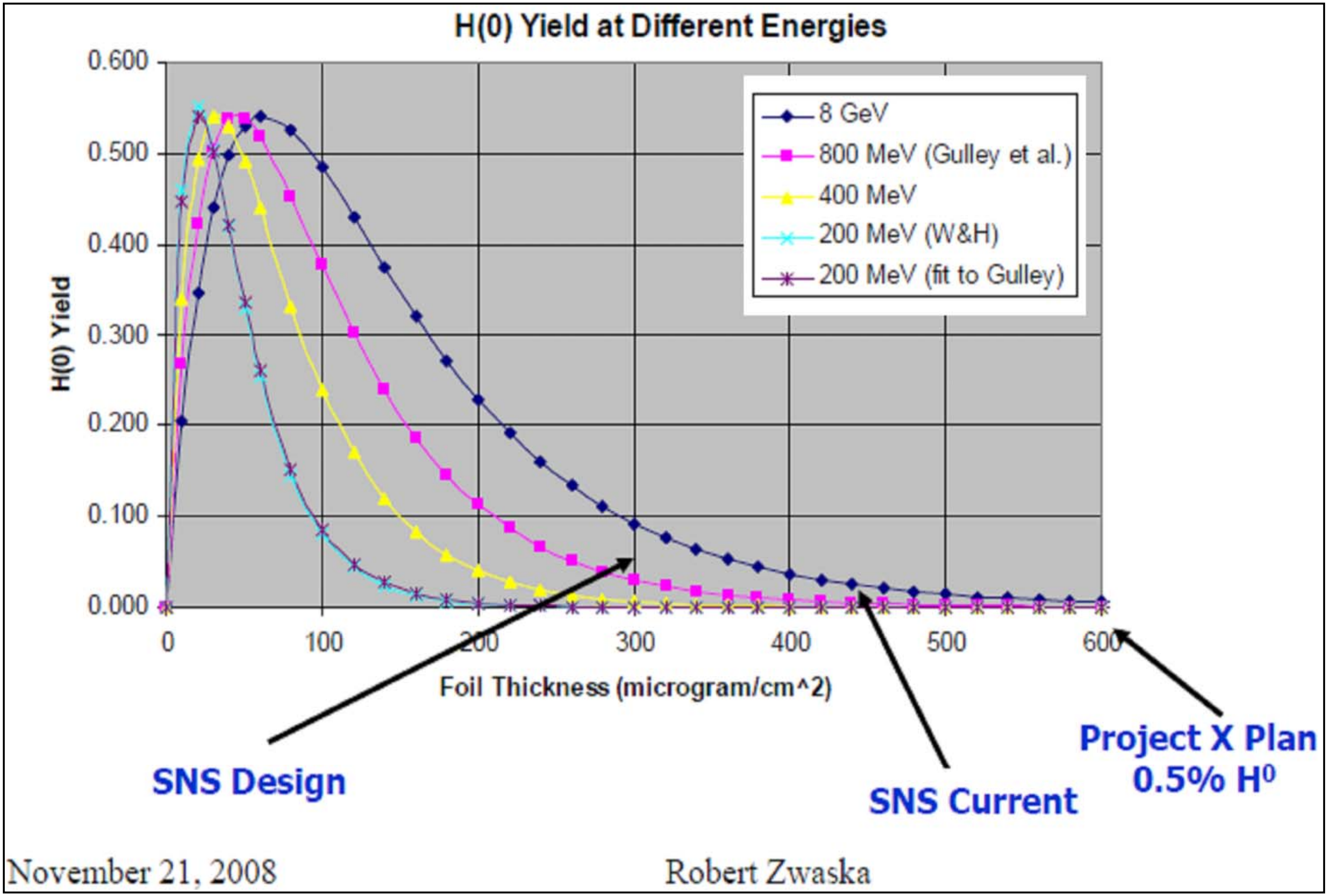

- Transverse painting is designed to
  - Minimize the number of secondary passages and foil heating
  - To make correlated x-y painting with radius increase for each next pulse
    - Injected beam does not move on foil
    - Closed orbit describes almost a quarter of circle (forward and back)




- Injected beam phase space matched to the stored beam phase space:

$$\beta_{linac} = 0.345\beta_{ring} \; , \quad \alpha_{linac} = 0.345\alpha_{ring}$$

# Carbon foil strip injection to Recycler (continue)



# Carbon foil strip injection to Recycler (continue)

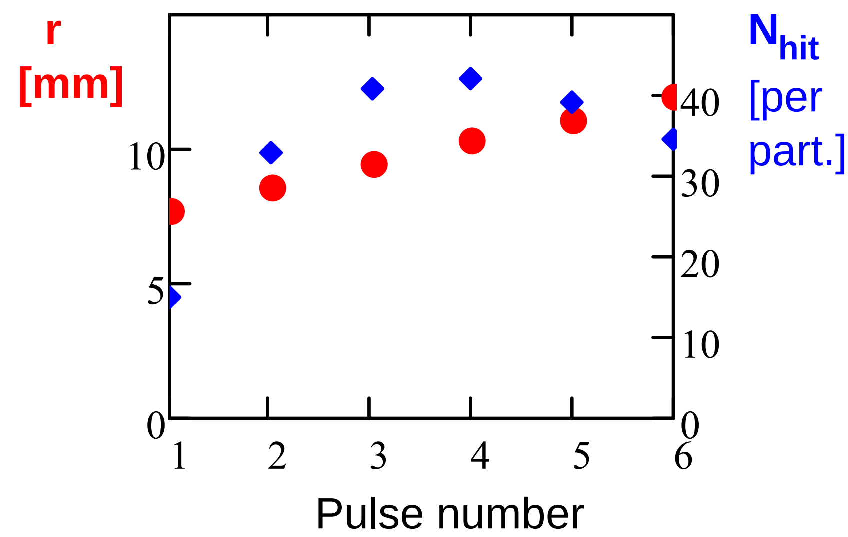
## *Beam and painting parameters*

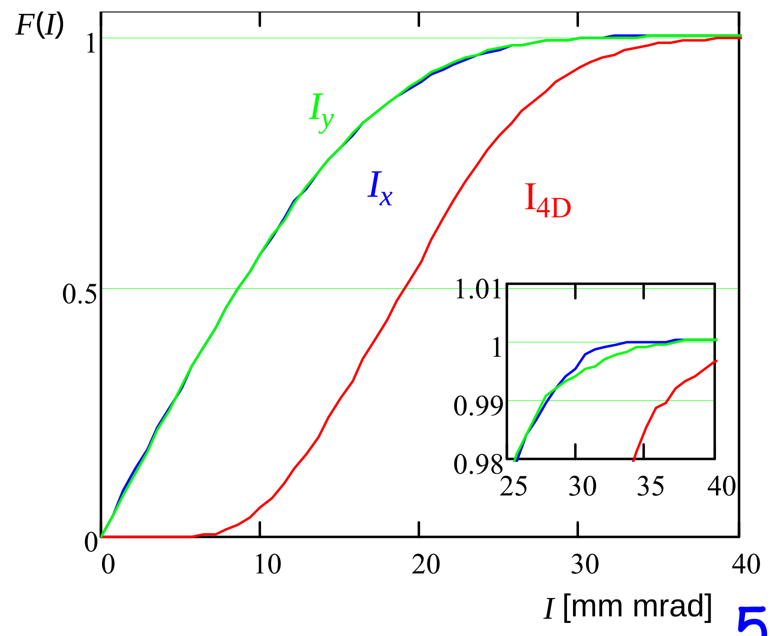
| | |
|---|---|
| Linac current | 1 mA |
| Pulse length | 4.2 ms |
| Number of pulses | 6 |
| Repetition rate | 10 Hz |
| Ring β-functions, $\beta_x=\beta_y$ | 60 m |
| Rms norm. linac emittance | 0.5 mm mrad |
| Norm. ring accept.@ 8 GeV | 40 mm mrad |
| Thickness of carbon foil | 600 μg |
| Power lost at injection with 0.8 s MI cycle | 9 kW |

## *Particle loss*

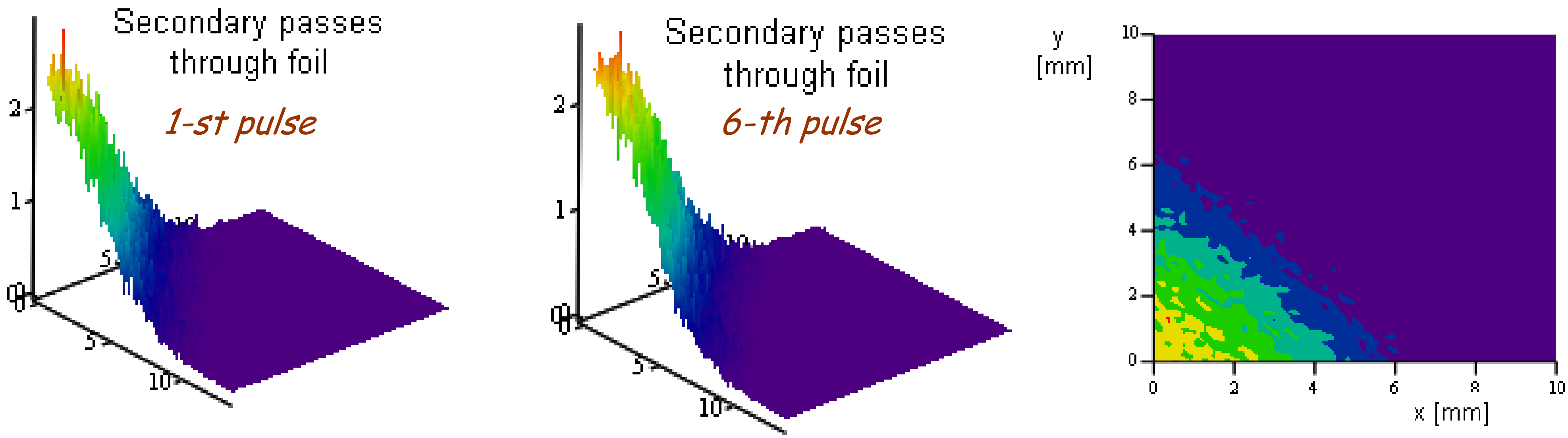
| | |
|---|---|
| Missing foil | 2.2% |
| Single scattering | 0.24% |
| Multiple scattering | 0.5% |
| Not stripped | 0.5% |
| **Total** | **3.5%** |

Number of foil hits per particle of single injection pulse



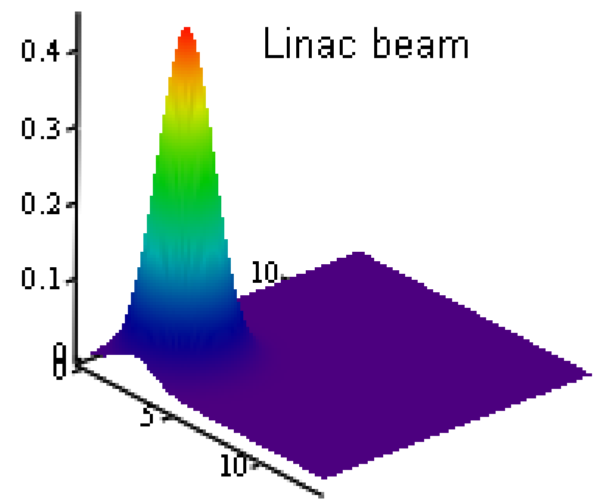



# Carbon foil strip injection to Recycler (continue)

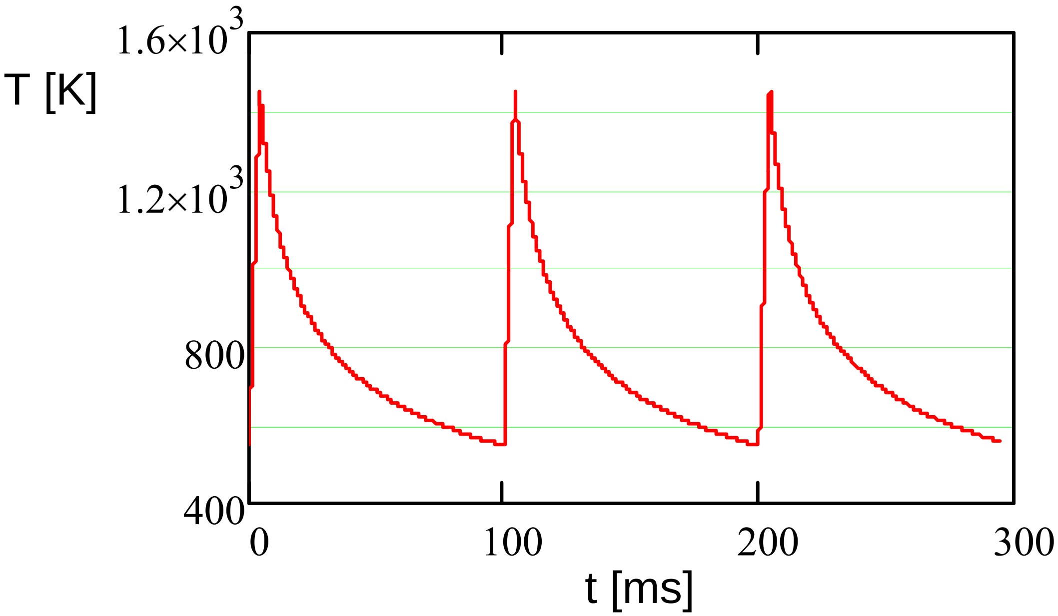


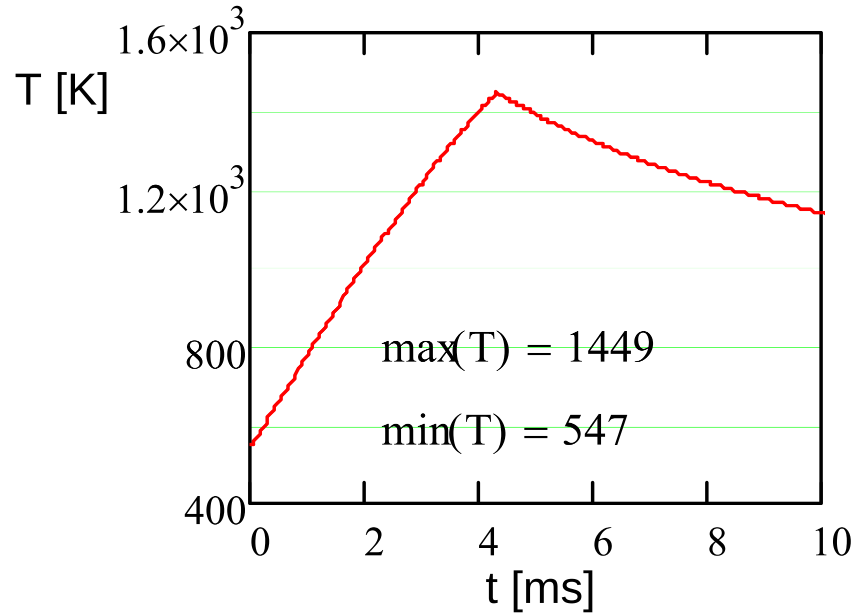

*Density of particle passes through foil (mm$^{-2}$ per particle of single pulse)*

- Foil heating by linac beam is ~20% of foil heating due to secondary passages of stored particles
- To increase radiative foil heating the foil is tilted by 45% deg. relative to the beam direction
  - 25% of power is removed by δ-electrons



# Carbon foil strip injection to Recycler (continue)



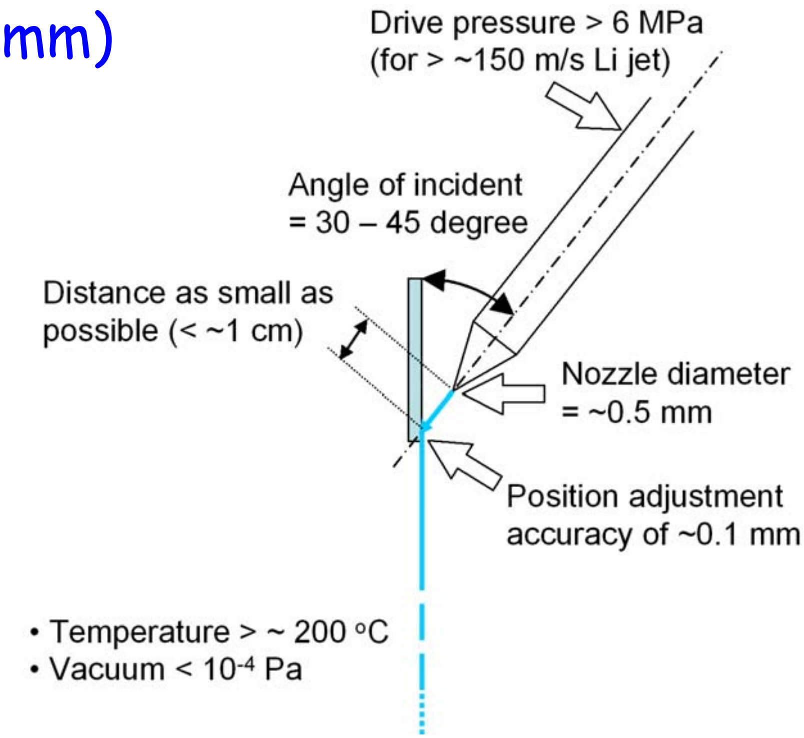



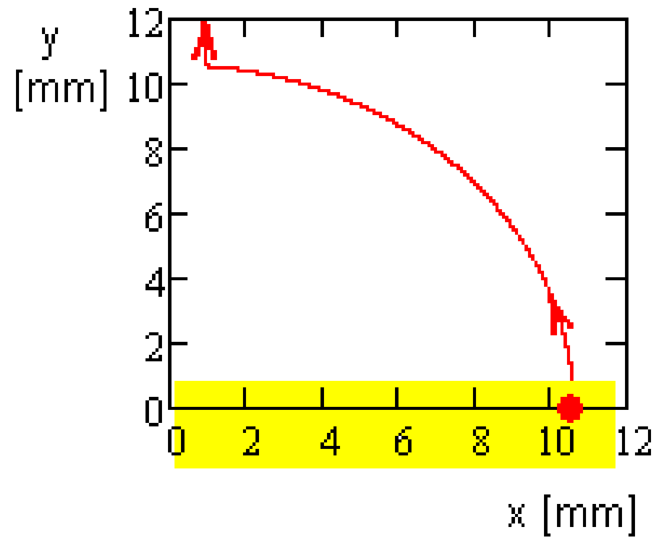

*Dependence of maximum foil temperature on time, only radiative cooling is taken into account*

- With chosen parameters the foil temperature stays <1150 C°
  - Required for good reliability
- Increase of β-functions at the foil would reduce the power density and foil temperature but increases beam loss due to single scattering
- Injection at 8 GeV looks possible but does not look as pretty as 2 GeV injection to RCS
  - ~4 times larger beam power loss at injection (8 GeV / 2 GeV)

# Strip-injection to Recycler through thin liquid Li thin film*

- Li stream is formed by a nozzle (Ø 0.5 mm)
  - Pressure ~5 MPa (50 atm), v ≈ 130 m/s
  - Entire beam is painted in one pulse
  - Twice larger thickness (1.3 mg/cm$^2$) to achieve stripping inefficiency of ~0.5% (as for carbon foil)
- One pass circular X-Y painting is used
  - ~4 times larger number of secondary hits
    - 1.3% single scattering loss
  - In difference to carbon foil it has negligible heating, ΔT~5 K°
- In experiments carried out in ANL the stream edge was not quite stable and had significantly larger thickness
  - Has to be resolved for beam stripping in a ring
- Reliability, vacuum, etc. ???

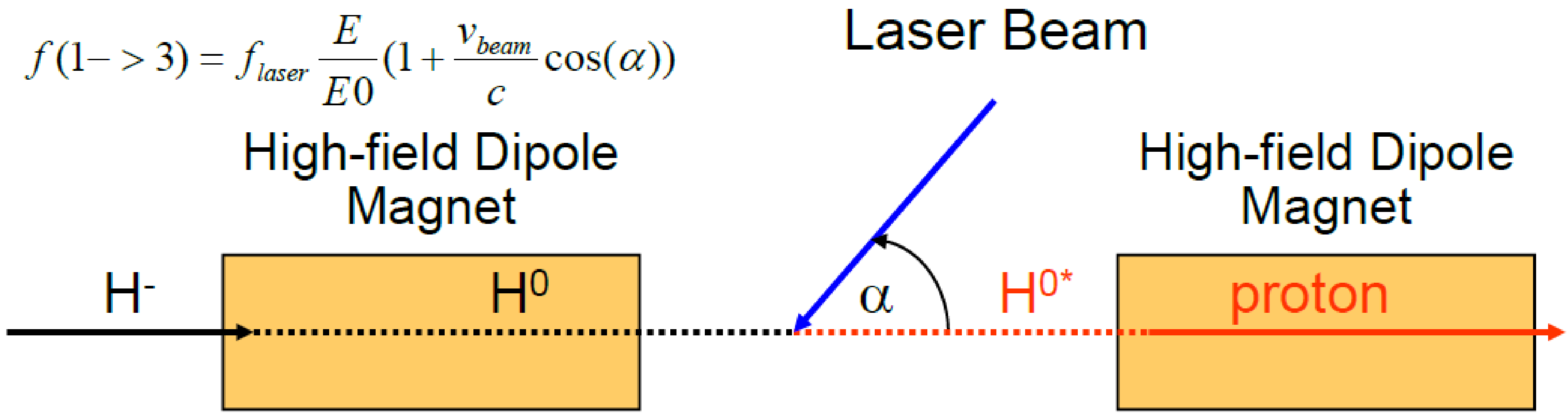



* Y. Momozakia;1 J. Nolen,b C. Reed,a V. Novicka and J. Specht, ANL

# Laser Assisted Stripping to Recycler (Danilov, PRST 6, 053501)

$$f(1->3) = f_{laser}\frac{E}{E0}\left(1+\frac{v_{beam}}{c}\cos(\alpha)\right)$$



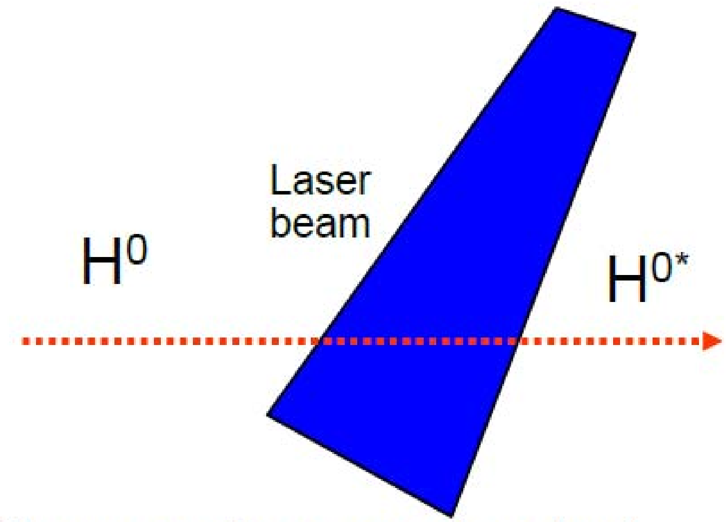

| Step 1: Lorentz Stripping | Step 2: Laser Excitation | Step 3: Lorentz Stripping |
|---|---|---|
| $H^- \rightarrow H^0 + e^-$ | $H^0$ (n=1) + $\gamma \rightarrow H^{0*}$ (n=3) | $H^{0*} \rightarrow p + e^-$ |

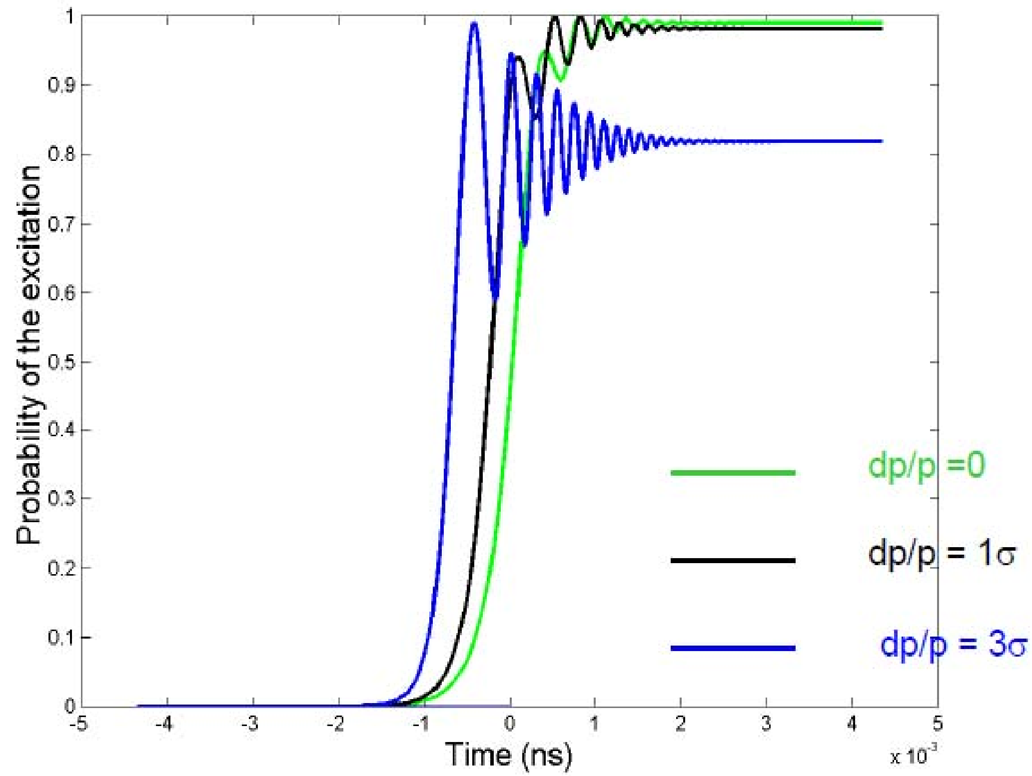
- 3 step stripping reduces the laser power to a practical value
  - Cross section of resonance excitation is much larger
    - SNS plans to use n=3 at 1 GeV ($\gamma$=2)
    - $\sigma$ decreases with n encrease

      $\Rightarrow$ n=2 is preferable for 8 GeV
      - Lorentz stripping from n=2 is not a problem for 8 GeV
  - Both Lorentz strippings introduce an emittance growth

# Laser Assisted Stripping to Recycler (continue)

- Laser beam divergence introduces an adiabatic transition and switches off transition selectivity due to Doppler effect

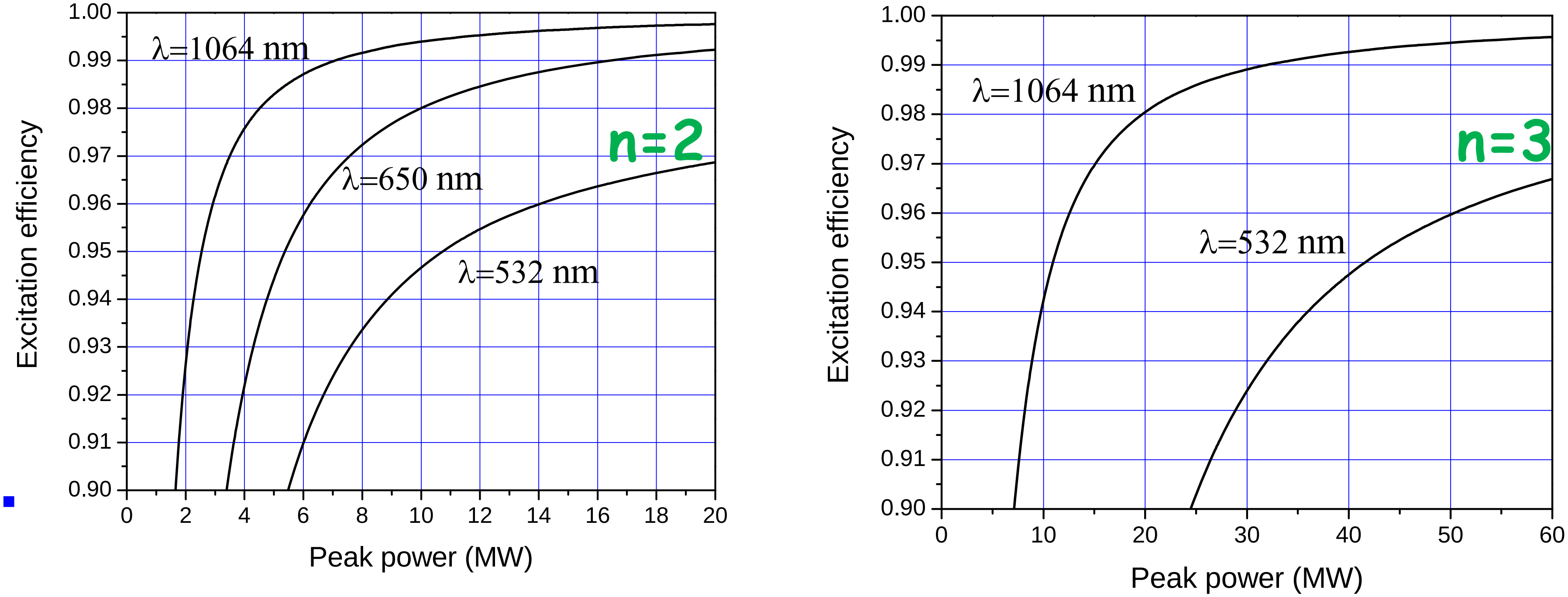



- The quantum-mechanical two-state problem with linearly ramped excitation frequency shows that the excited state is populated with high efficiency

- To suppress the Stark effect the laser polarization is chosen to be normal to the E-field excited by B-field in the beam frame
  - Vertical polarization for vertical B-field and horizontal crossing

# Laser Assisted Stripping to Recycler (T. Gorlov, SNS)




## Parameters used to build the above pictures

| Level | n=2 | | | n=3 | |
|---|---|---|---|---|---|
| Wavelength, nm | 1064 | 650 | 532 | 1064 | 532 |
| Incidence angle, deg | 94.63 | 116.14 | 122.90 | 84.81 | 117.23 |
| Peak power, $P_0$, MW | 5 | 10 | 30 | 20 | 110 |
| Micropulse energy, mJ | 1.0 | 2.0 | 6.7 | 4.5 | 25.6 |
| Power for 325 MHz, MW | **0.23** | 0.46 | 1.5 | 1 | 6 |
| Micropulse duration, $\sigma_\tau$ rms, ps | 84 | 85 | 90 | 91 | 93 |
| x - rms size, $r_x$, mm | 2.5 | 9.5 | 2.6 | 7.1 | 7.1 |
| y - rms size, $r_y$, mm | 2.0 | 1.8 | 2.4 | 2.0 | 2.0 |
| x -divergence, $\alpha_x$, mrad | 0.7 | 0.3 | 0.3 | 0.6 | 0.3 |
| y -divergence, $\alpha_y$, mrad | 1.9 | 1.1 | 1.7 | 1.3 | 1.4 |

$\beta_x$=40 m
$\beta_x$=10 m
$D_x$=$D_y$=0
$\sigma_{\Delta p/p}$=$2.5\cdot10^{-4}$
$\varepsilon_{x,y\ norm}$=0.5 mm mrad
$\sigma_{\Delta t(H^-)}$ = 65 ps

## Laser Assisted Stripping to Recycler (continue)

- Emittance growth is ≤ 0.7 mm mrad (norm. rms)
- Overall stripping inefficiency is ~5%
  - A spontaneous decay from upper level contributes ~3%
- High Q laser resonator reduces the laser power to acceptable level
  - Pumping through laser dielectric windows with R=99.98%
  - Quality factor $1.5 \cdot 10^4$
    - $10^5$ was demonstrated in the NIST experiments
  - Cavity length 184.5 cm (4-th subharmonic of 325 MHz)
  - Cavity filling time 30 μs
  - Average laser power 3 W
    - $P_{peak}$=230 kW, $\lambda$=1.064 μm, $f_{rep}$=10 Hz, $T_{pulse}$=4.2 ms
  - Such a cavity was never used in high radiation conditions
    - Reliability and stability of operation are unknown

# Summary of beam injection to Recycler

- Small emittance of the linac beam improves injection efficiency and quality of the stored beam
- Foil strip injection looks feasible
  - It has been operating in SNS and proved to be effective
  - Requires multiple pulses from linac for one Recycler fill
    - 10 Hz & 4.2 ms look as a reasonable choice
- Injection through liquid lithium film requires improvements of film quality
  - It is not obvious that these improvements can be achieved
- Laser assisted stripping looks promising
  - Requires real experimental verification
    - Collaboration with SNS can help
  - Both single pass and multiple pass injection can be supported

# Injection Issues to NF and MC

- Limitations on the linac parameters and beam structure come from
  - $H^-$ beam stripping
  - Bunch compression

# Bunch compression

- Very large beam loading
  - ⇒ Two rings: Accumulator & Buncher
    - o This choice addresses questions
      - how to create the bunching RF field much faster than the synchrotron period
      - Beam loading to bunching RF system during beam storage
- Barrier-bucket RF in Accumulator
  - ♦ Operation with zero-slip factor (CERN) is prevented by the transverse-longitudinal instability*

    E. Pozdeyev, PR-ST 12, 054202 (2009)
- RF voltage in Buncher cavities is excited to full amplitude at beam injection
  - ♦ Reduces power requirements

---

*An estimate was done by A. Burov

# Bunch compression (continue)

- Longitudinal micro-wave instability limits the length of the bunch accumulated in Accumulator

$$\sigma_p{}^2 L_b \ge \frac{r_p N}{\eta\gamma^3} \xrightarrow{\varepsilon_{\|}=\gamma\sigma_p L_b} L_b \ge \frac{r_p N}{\eta\gamma\varepsilon_{\|}{}^2}$$

  $\Rightarrow$ For muon collider parameters the initial bunch length in accumulator ring < C/4 (8 GeV)

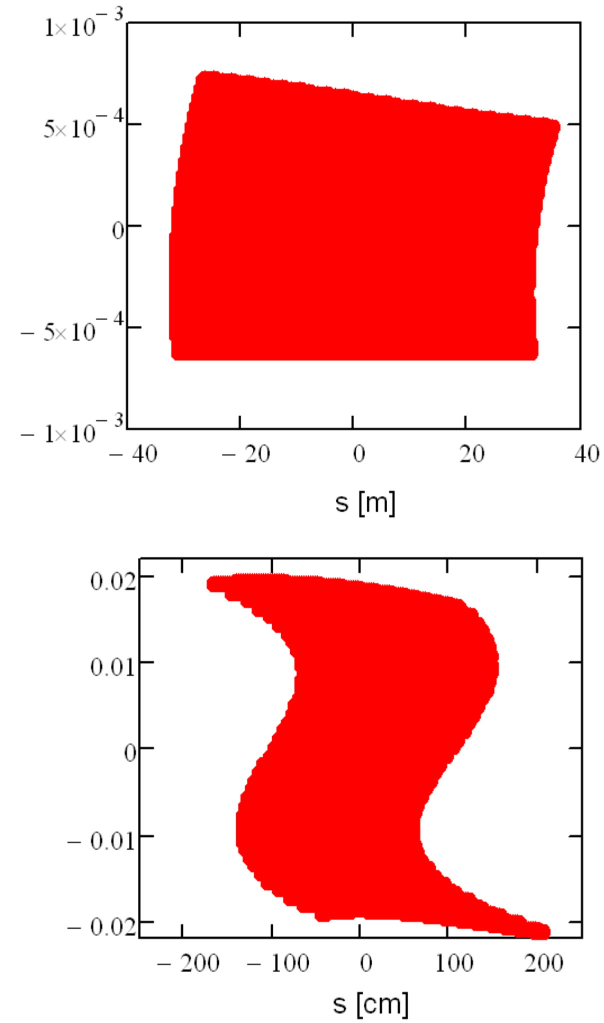
- Adiabatic bunch compression looks questionable even at NF intensity
  - + Linearity of bunch rotation easier to achieve for initially short bunch
- All this favors small initial bunch length: $L_b < C/4$

  $\Rightarrow$ Increases peak current of the linac in the same proportion

# Bunch compression (continue)

## Injection and Bunch Compression for NF

| | |
|---|---|
| Beam energy | 8 GeV |
| Circumference | 264 m |
| Transition energy | 3.9 GeV |
| Acceptance, mm mrad | 200 |
| Momentum acceptance | ±3% |
| Linac current, peak/average, mA | 20/5 |
| Linac rms momentum spread | $<2\cdot10^{-4}$ |
| Linac energy sweep | $\pm6\cdot10^{-4}$ |
| Filling factor, $L_b/C$ | 0.25 |
| Total injection time | 1.7 ms |
| DC beam current in the ring | 9.6 A |
| Number of particles | $5.3\cdot10^{13}$ |
| Harmonic number, h | 1 |
| $(Z_n/n)_{Space\ charge} = (Z_n/n)_{Stability}$ | 10 Ω |
| Repetition rate | 60 Hz |
| Beam power | 1 MW |



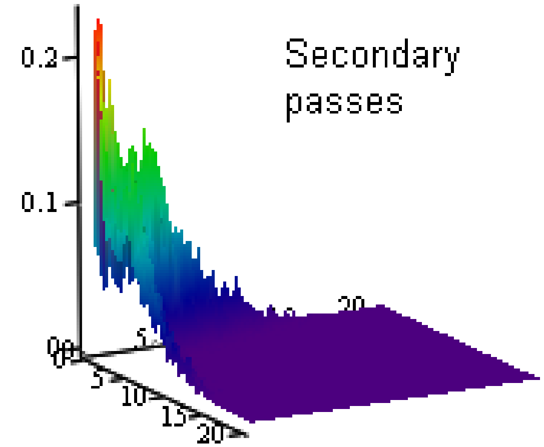

*Longitudinal phase space at the end of injection and after compression*

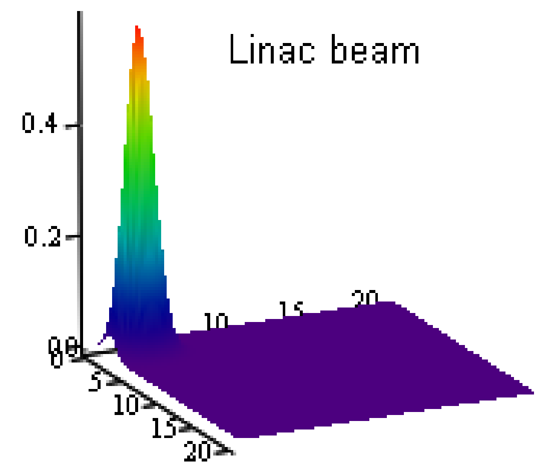
- 4 MW in MC is achieved by combining four bunches at the target at 15 Hz rep. rate

# Strip-Injection to NF/MC Accumulator Ring

- Foil-strip injection
  - Impossible for both NF & MC for 1 mA linac current
    - Linac current increase to ~5 mA is required for NF
    - Large acceptance greatly reduces the foil heating

| | |
|---|---|
| Number of injection turns | 2000 |
| Beta-functions on the target | 10 m |
| Rms linac size on the target | 1 mm |
| $\varepsilon_{95\%\ n}$ for stored beam, mm mrad | 1300 |
| Number of injection turns | 2000 |
| Number of secondary passages per particle | 2.3 |
| Foil heating after 1 pulse | ~700 K |




  - 4 MW for MC can be done combining beams of 4 rings on the target

## Strip-Injection to NF/MC Accumulator Ring (continue)

- Laser assisted strip injection
  - Looks realistic for both NF & MC
  - 5% of beam loss (200 kW) represents considerable challenge
    - Laser stripping in the magnetic field can improve efficiency
      - SNS experience with laser stripping will be greatly helpful
  - Can work with both pulsed and continuous linac

# Conclusions for Power Limits in Buncher and Accumulator

- At 8 GeV and 15 Hz rep. rate the beam power from a single ring is limited to ~1 MW
  - 60 Hz makes 4 MW required for neutrino factory
  - Combination of 4 bunches at the target makes 4 MW at 15 Hz required for muon collider
- Laser stripping allows to use CW $H^-$ beam
- Foil stripping requires pulsed beam with average beam current of ≥5 mA and peak beam current ≥20 mA

# Conclusions

- Making Project X more compatible with Muon Collider - Neutrino Factory needs requires
  - additional investment
  - affects other intensity frontier experiments and
  - complicates the design of the accelerator complex
    - RCS -> to 3-8 GeV pulsed linac
    - ~4 times larger power lost at injection
    - …
- If the MI neutrino program has the highest priority

  $\Rightarrow$ 2 GeV CW linac and RCS look as the right choice
- Would it be wise step to make the Project X, MC and NF more collinear?