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ESS NEUTRINO SUPER BEAM

Funded by the Horizon 2020 Framework Programme of the European Union

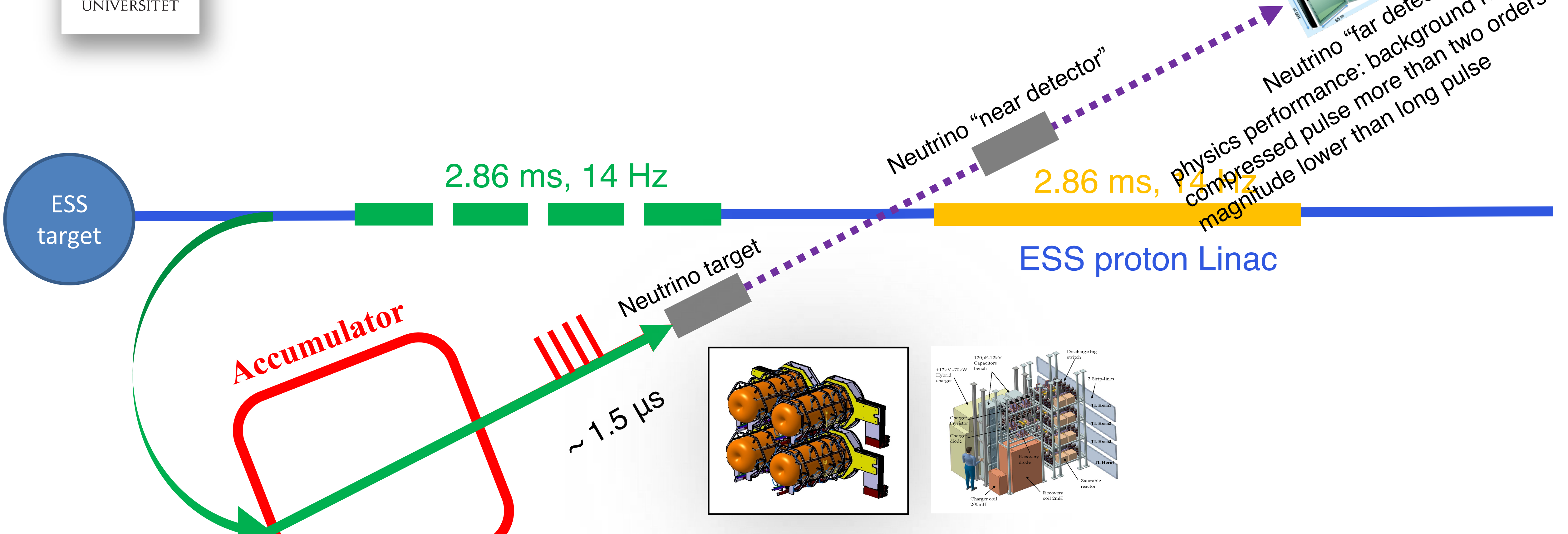
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

The ESSnuSB accumulator design

Ye Zou, Uppsala University, on behalf of WP3

The ESSnuSB Workshop,
October 8 - 9, 2020
Hamburg, Germany

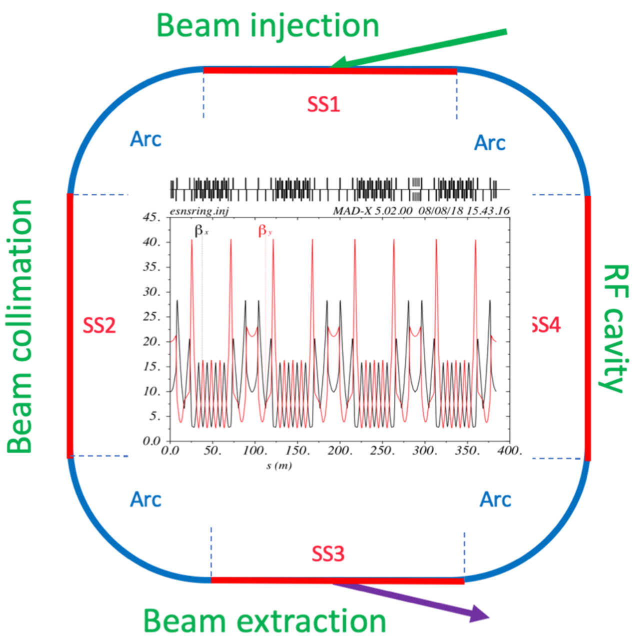
Why do we need an accumulator ring?



Ohmic heating of the horn limits the duration of the pulse impinging the target

The accumulator ring design

- Pulse from ESS Linac: 2.86 ms, 2.5 GeV, 5 MW
- Pulse required by neutrino target: ~1.5 μs 4 sub-pulses, 1.25 MW for each target
  - Ring circumference: ~ 400 m
  - Injection turns: ~ 600
  - Extraction gap: ~100 ns
  - Total beam loss (1 W/m): <10^{-4}
  - Collimation efficiency: >90%
  - Space-charge tune shift: <0.1



- Lattice developed by Horst Schönauer
- Circumference: 384 m
- 4-fold symmetry
  - 4 straight sections SS1~SS4 (red line) + 4 arc sections Arc (blue line)
  - 4 straight sections (red line) are for beam injection, collimation, extraction, and RF.
- Fixed injection chicane (9 cm) and fast programmable bump for injection painting

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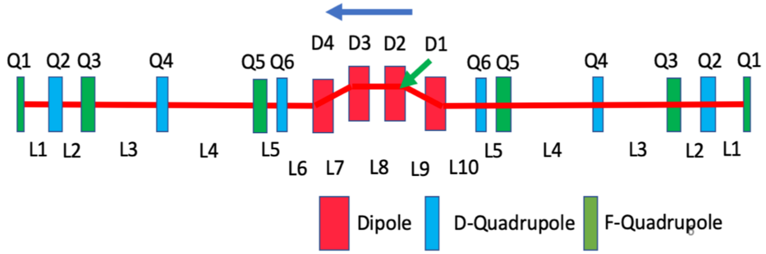
Beam injection



- H^- injection

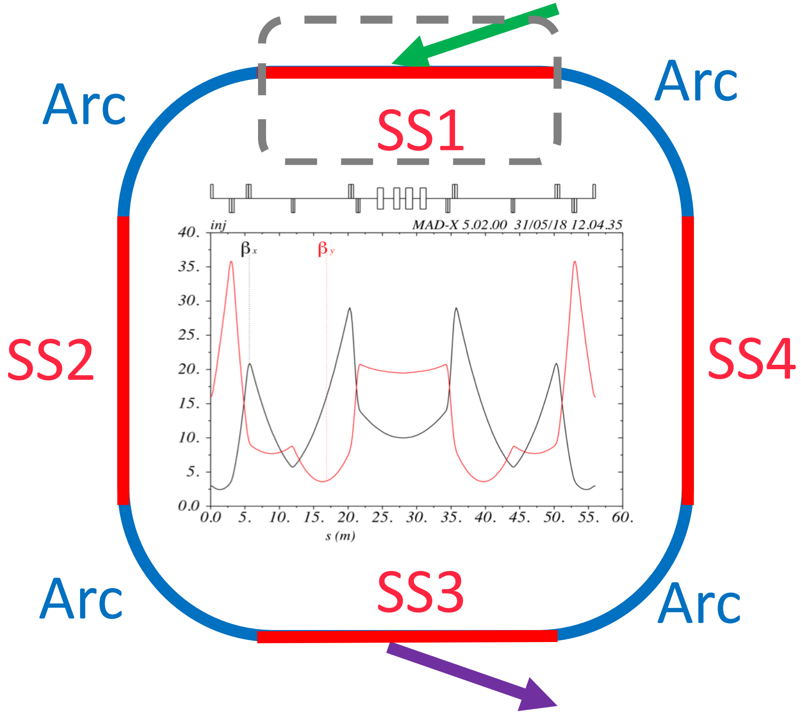
- H^- injection: Non-Liouvillean, proton can be overlaid on H^- in phase space, very high beam intensity can be injected to the accumulator

- Foil stripping or laser stripping?

- Foil stripping: widely used in proton synchrotrons or accumulators, very challenging to ESSnuSB
- Laser stripping: a promising alternative method

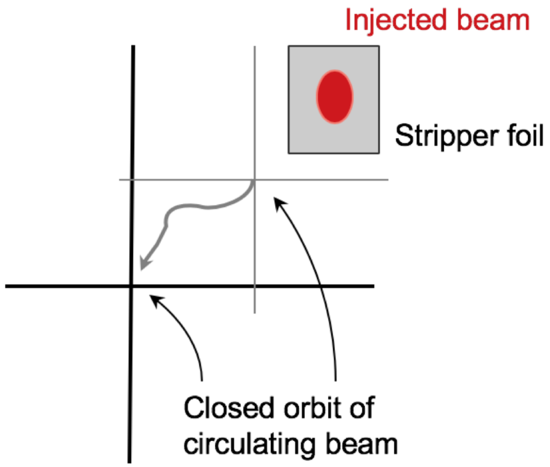
- Painting

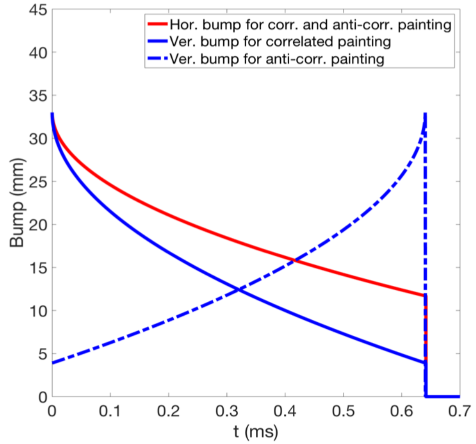
- Mitigate space charge issue
- Mitigate foil temperature issue

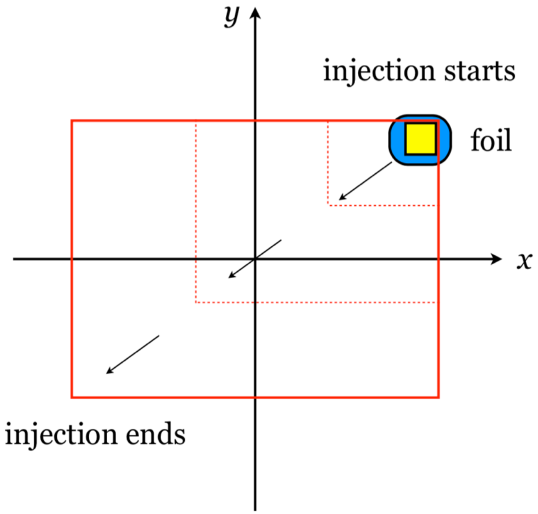


Beam injection: painting

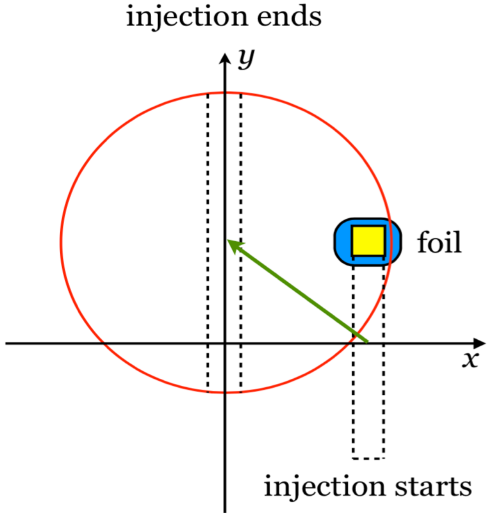
- Painting to a "large" beam size can reduce space charge effect and peak foil temperature
- Painting methods: varying the injection point or angle; moving closed-orbit of circulation beam at the foil by programming orbit bumps in both H and V planes
- Painting types: correlated painting and anti-correlated painting







Correlated painting

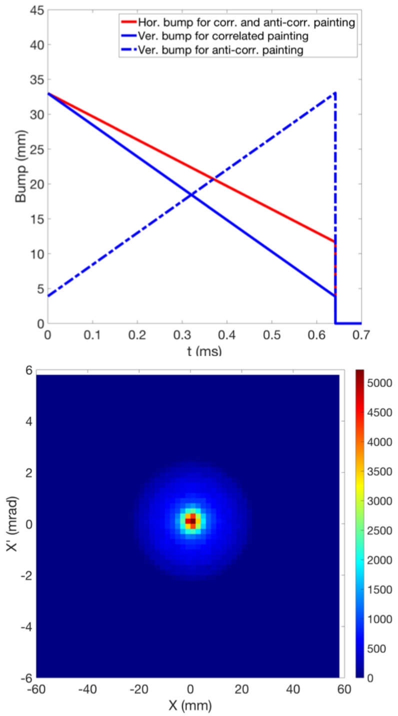


Anti-correlated painting

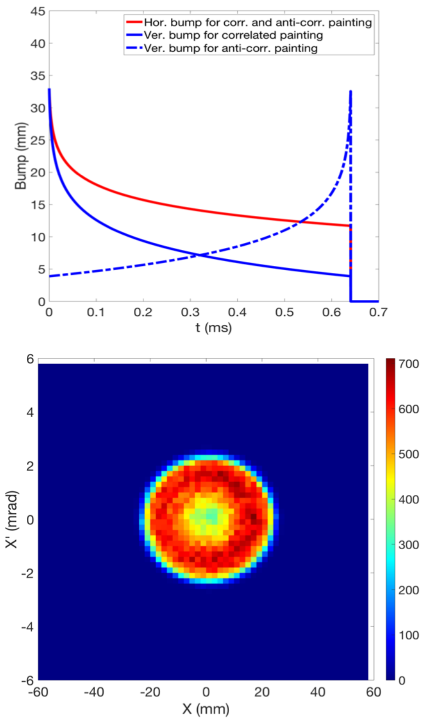
How to achieve good painting?

- Optimize the painting process to get beam distribution that we need
  - Can mitigate space charge issue
  - Can mitigate foil temperature issue
  - Can satisfy requirements from the target
  - Beam should be stable in the accumulator

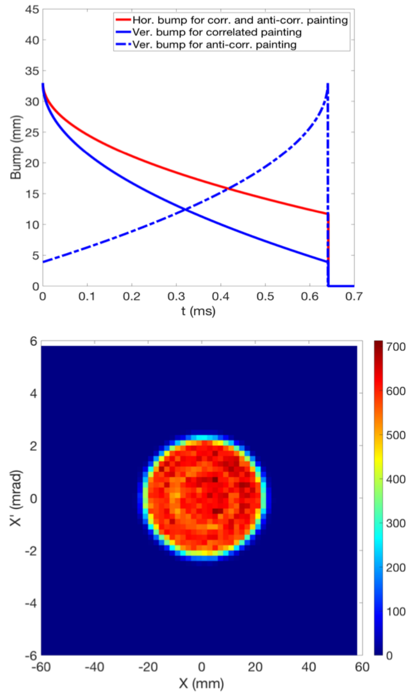
Less painting



Over painting

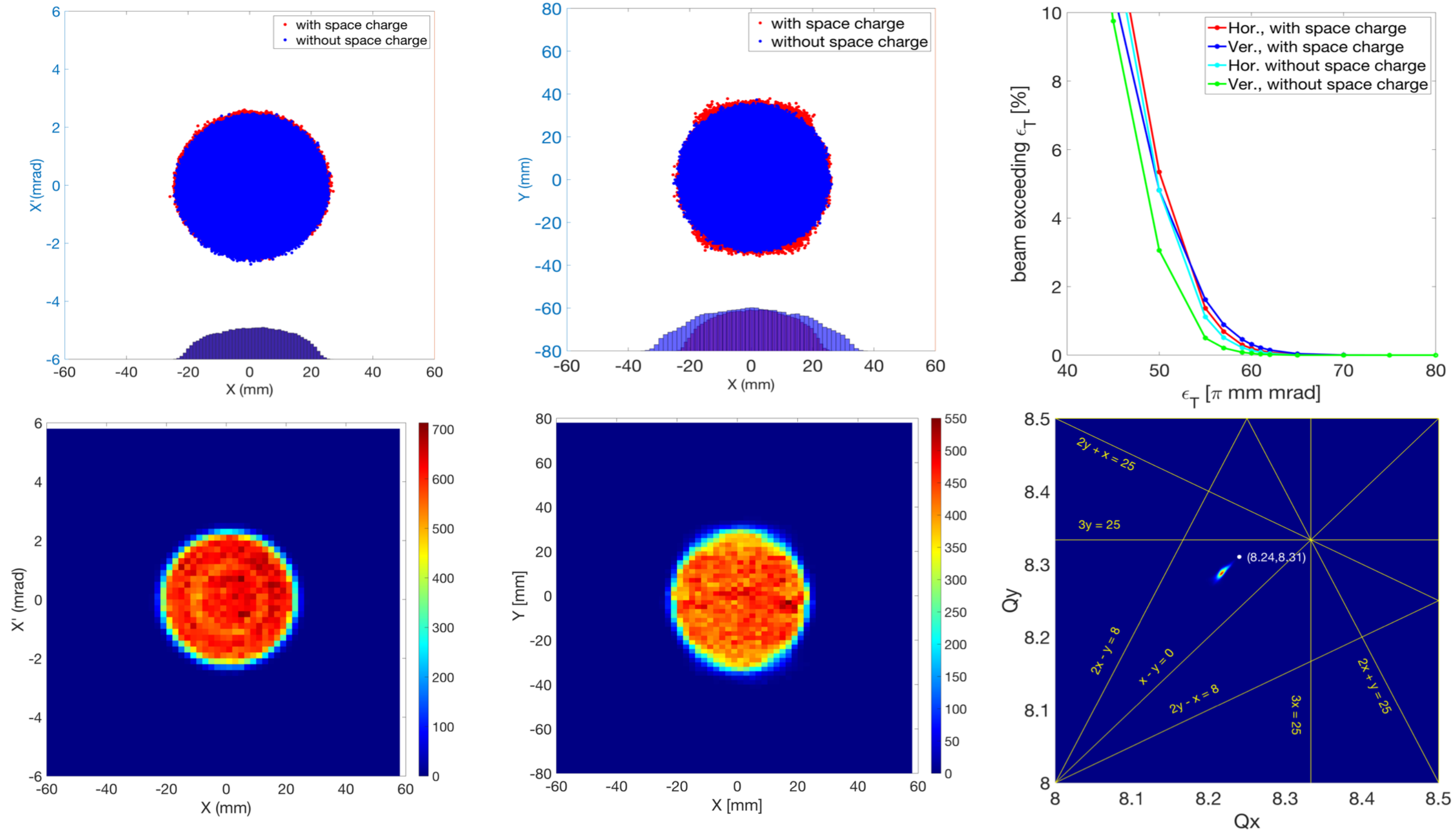


Good painting



An example of painting results for ESSnuSB AR

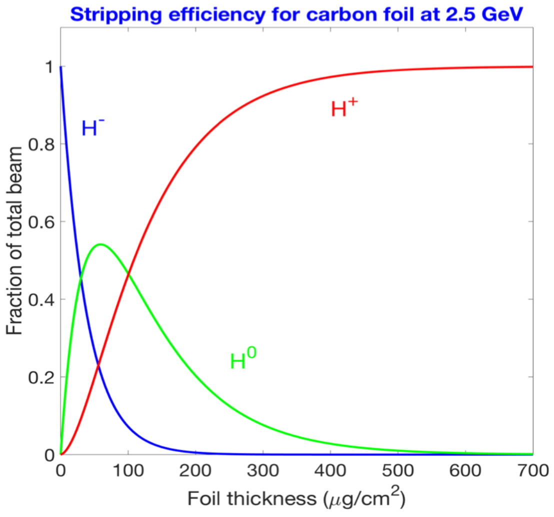
Basic parameters for simulations	Value
Hor./Ver. Norm. rms emittance	0.35 mm mrad
Extraction gap	133 ns
Energy spread, 1 sigma	0.02%
Foil thickness	500 μg/cm^2
Hor./Ver. beta function at injection point	10 m/ 20 m
Hor./Ver. tune	8.24/8.31
Injection turns	597
Macro particles per turn	500
Pulse length per turn	1.2 μs
Beam intensity per turn	3.7×10^{11}
Barrier RF voltage	5 kV
Barrier RF phase	162 deg



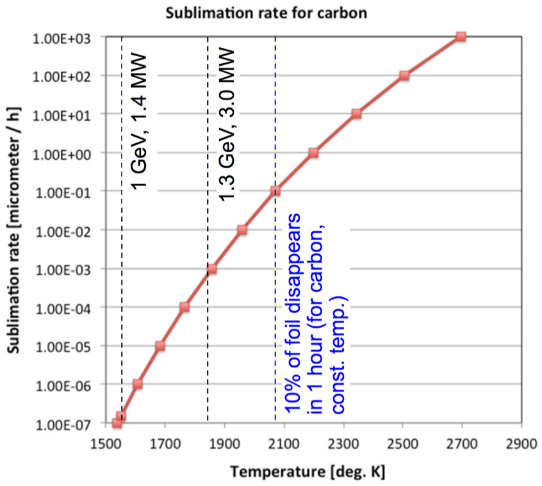
- Very small tune spread (~0.05), which fits the calculation results
- 100% beam emittance: 59 π mm mrad in horizontal and 60 π mm mrad in vertical plane
- RMS emittance: 12.9 π mm mrad in horizontal and 12.5 π mm mrad in vertical plane

Beam injection: foil stripping

- Foil stripping is widely used in proton synchrotrons and accumulators
- Stripping efficiency:
  - Take the carbon foil for instance, if stripping efficiency reaches 99%, the foil thickness should be at least 500 µg/cm^2
  - As the foil thickness increases, stripping efficiency increases, scattering increases, energy deposition in the foil increases
- Foil temperature:
  - If foil temperature exceeds 2000 K, the foil lifetime will be decreased sharply
  - We adopt several methods to mitigate the issue
- Foil scattering, causes residual radiation
- Stripped electrons, should be considered carefully



H- stripping cross section scaled from M.S. Gulley et al., Phys. Rev. A 53 (1996) 3201

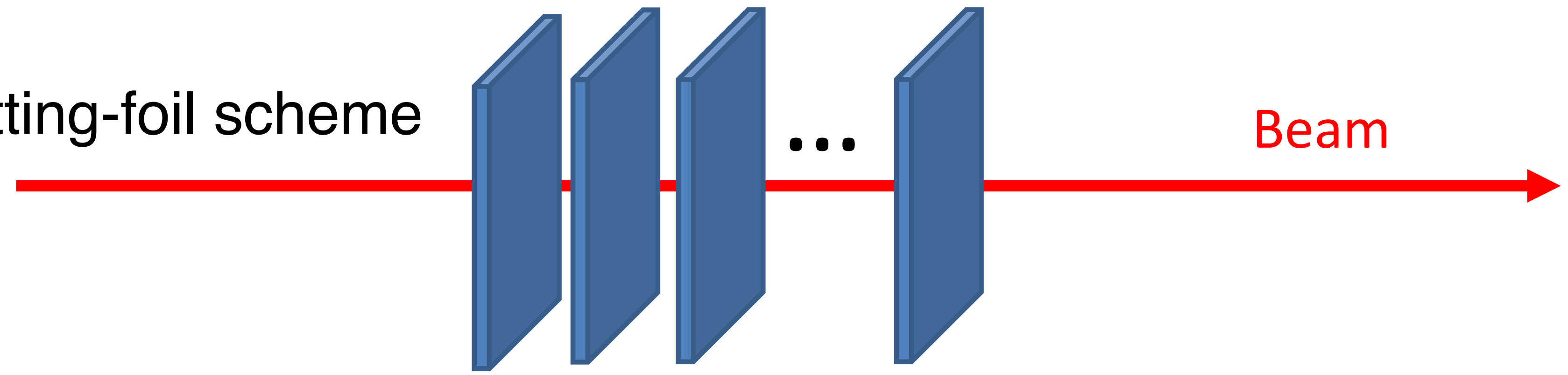


M. Plum, HB2016, Jul. 3-8, 2016

Foil temperature: a big challenge

- Foil temperature mainly comes from injection beam (center) and circulating beam (both center and inner corner/edge)
- Several methods are considered to mitigate the peak temperature on the foil:
  - Good painting can decrease the peak foil temperature at the inner corner
  - Splitting-foil scheme: splitting the foil into several thinner ones with the same total thickness along the beam, which can lower the peak temperature at both the center and corner
  - Mismatched injection to mitigate temperature issue
  - Moving injection point is also considered

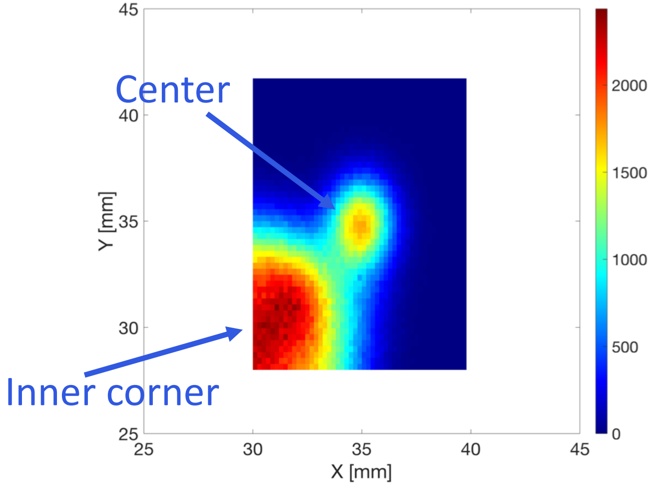
Splitting-foil scheme



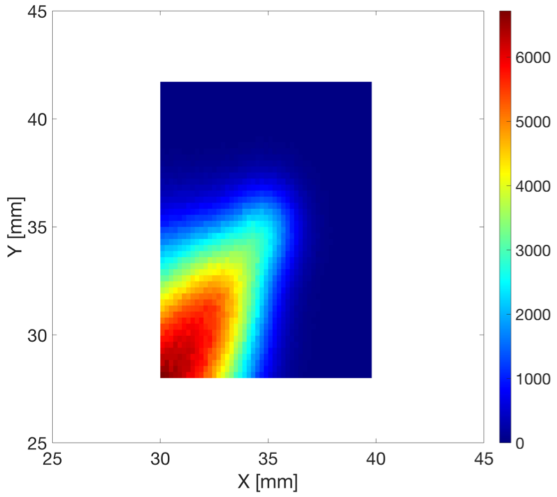
Foil temperature: a big challenge

- Two methods are used: painting and splitting-foil scheme
- Good painting and splitting-foil scheme (4 pieces) can dramatically reduce the peak temperature of the foil. However, the peak temperature still exceeds 2000 K.

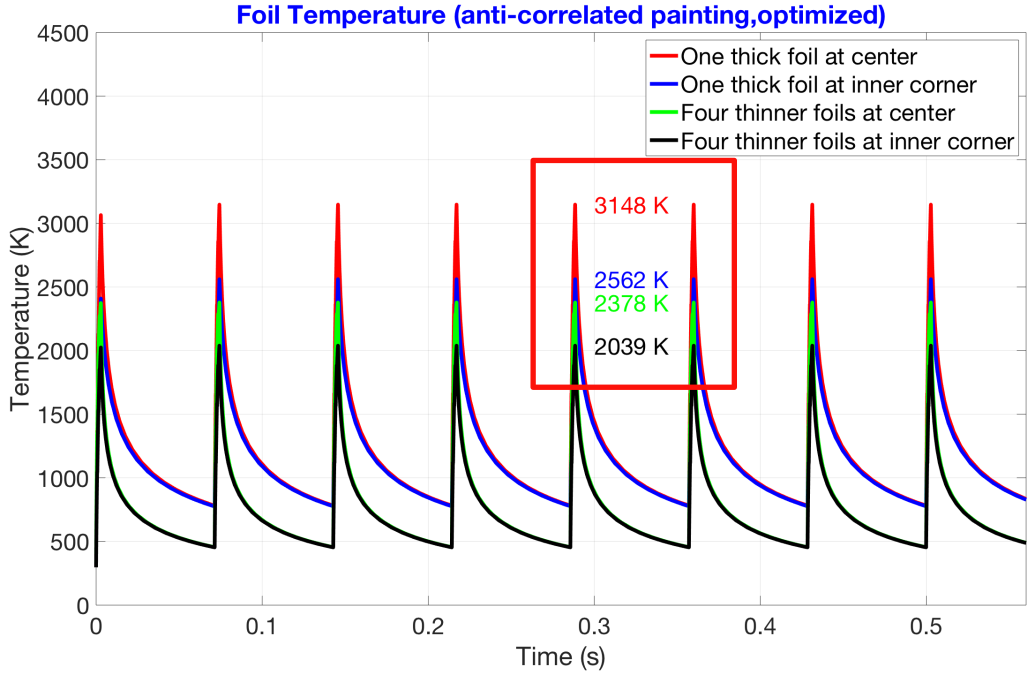
Good painting



Poor painting

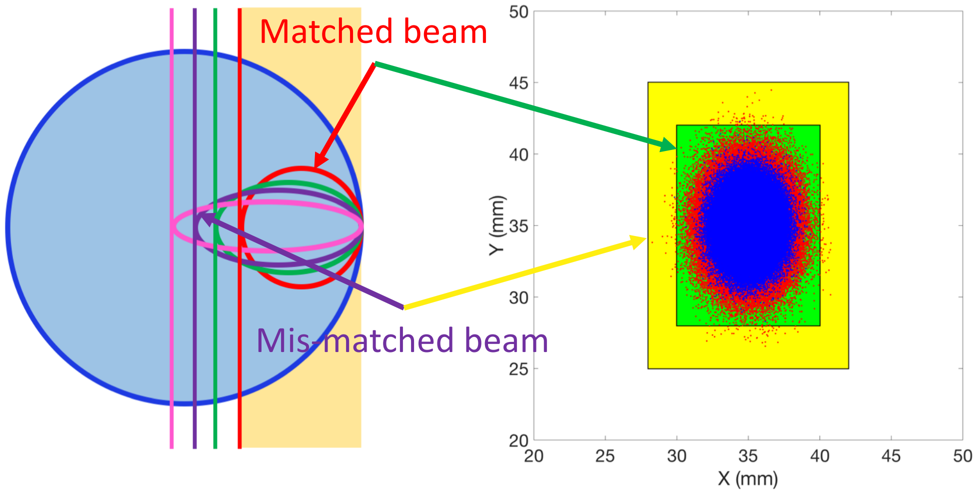


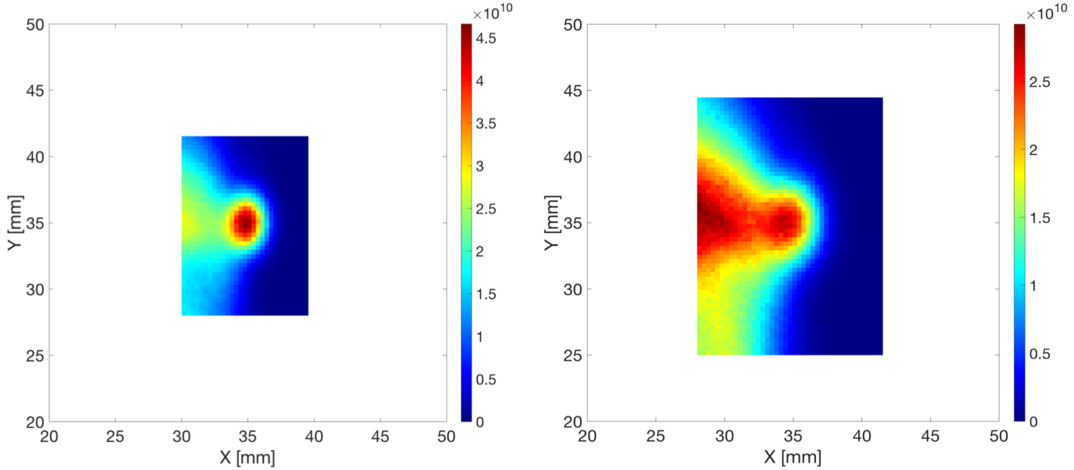
Beam foil-hits distribution (Corr. painting)



Mismatched injection

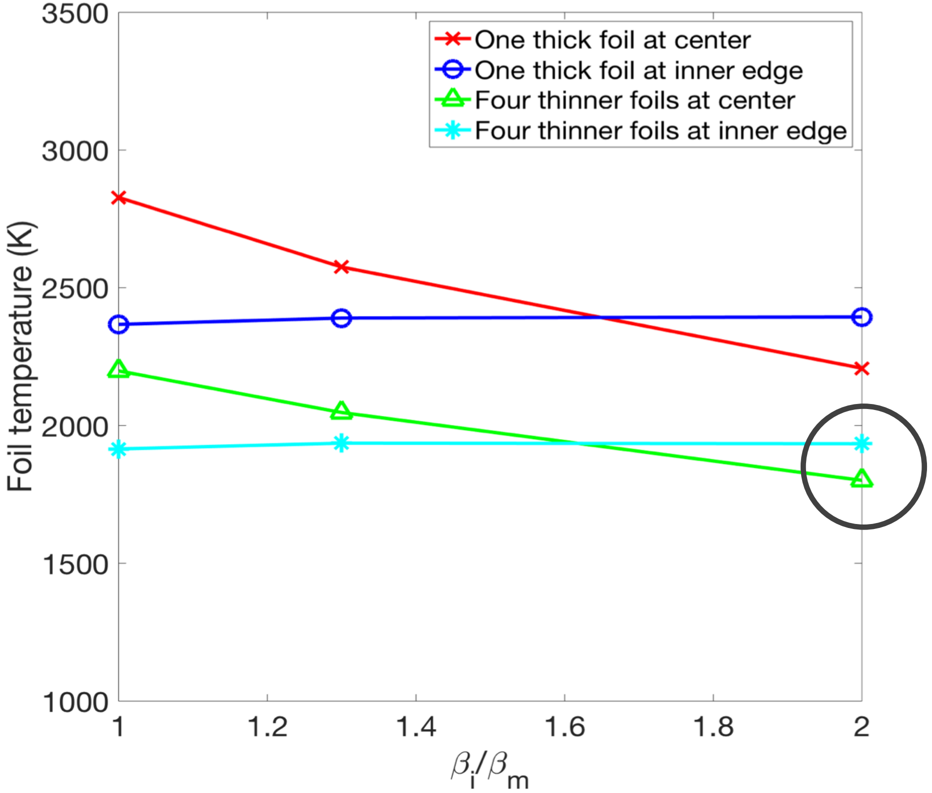
- Twiss parameter mismatch can be used as a tool to reduce the foil hits (with small injection spot size) or lower the foil temperature (with large injection spot size)
- Mismatch degree (β_i / β_m): β_i and β_m are beta function in the transfer line and in the ring at the injection point, respectively
- Mismatched injection needs foil in a larger size than matched injection and average foil hits will increase
- Peak energy deposition for mismatched injection (β_i / β_m =2) (2.4 × 10^{10} J/m^3) is much lower than matched injection (4.0×10^{10} J/m^3)

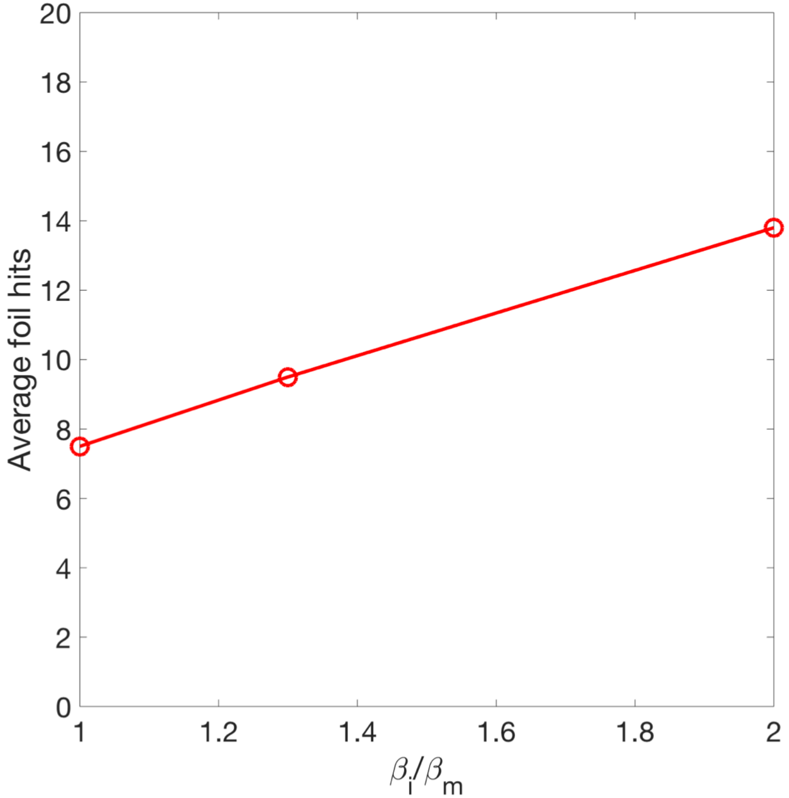




Energy deposition (4 batches) for matched (left) and mismatched (right) beam injection (Anti-corr. painting)

Optimized foil temperature





The maximum temperature can be lowered to 2000 K, if using good painting, mismatched injection at β_i / β_m=2 and with splitting-foil scheme (4 pieces).

Beam collimation

- Uncontrolled beam loss is a big issue for high-power, high-intensity accumulators: could cause equipment damage and residual activation, make hands-on maintenance unavailable
- Target: total beam loss (1 W/m) $<10^{-4}$, collimation efficiency > 90%
- Beam loss and control
  - Beam injection: non-stripped H- or partially stripped H0, large angle nuclear scattering
    - Beam dump for injection and dedicated collimators after injection region
  - Beam halo: particles with large amplitude or momentum deviation have risk being lost in the ring
    - Collimation system is needed to localize beam loss to a specific region which has strong shielding
  - Beam extraction: aperture restriction
    - A large aperture can minimize the beam loss at extraction

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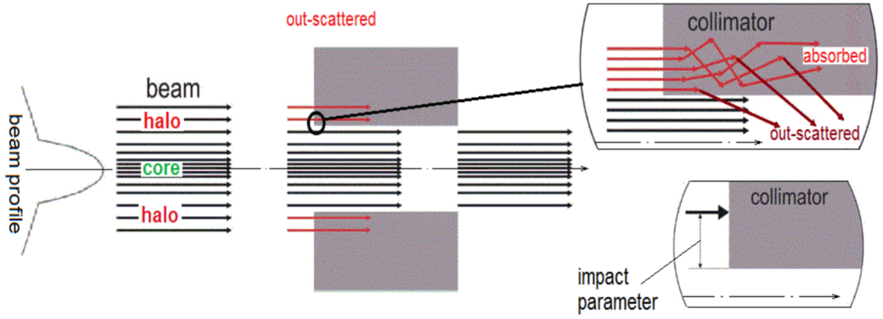
Two-stage collimation system

- The main purpose of a beam collimation system is to clean beam by removing all halo particles
- A certain fraction of the intercepted beam will survive, either by traversing the whole length of the block or by being scattered out of the side against the beam
- The impact parameter strongly influences the absorption efficiency of a single collimator jaw
- To reduce leakage of the particles due to the out-scattering, we need to increase the impact parameter
- A thin scraper is added before the thick collimators, so that the impact parameter of the scattered particles at the secondary collimator is significantly enlarged



Transverse distance from the edge of the collimator to the impact point of the halo particle

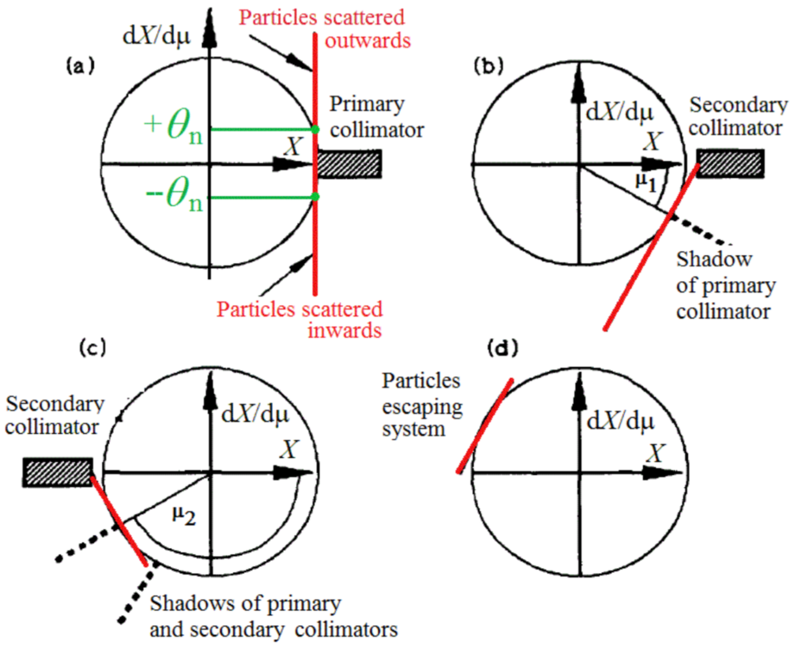
I. Strasik, “Machine Protection”, Lecture at CERN Accelerator School, Prague, Czech Republic,2014

Beam collimation

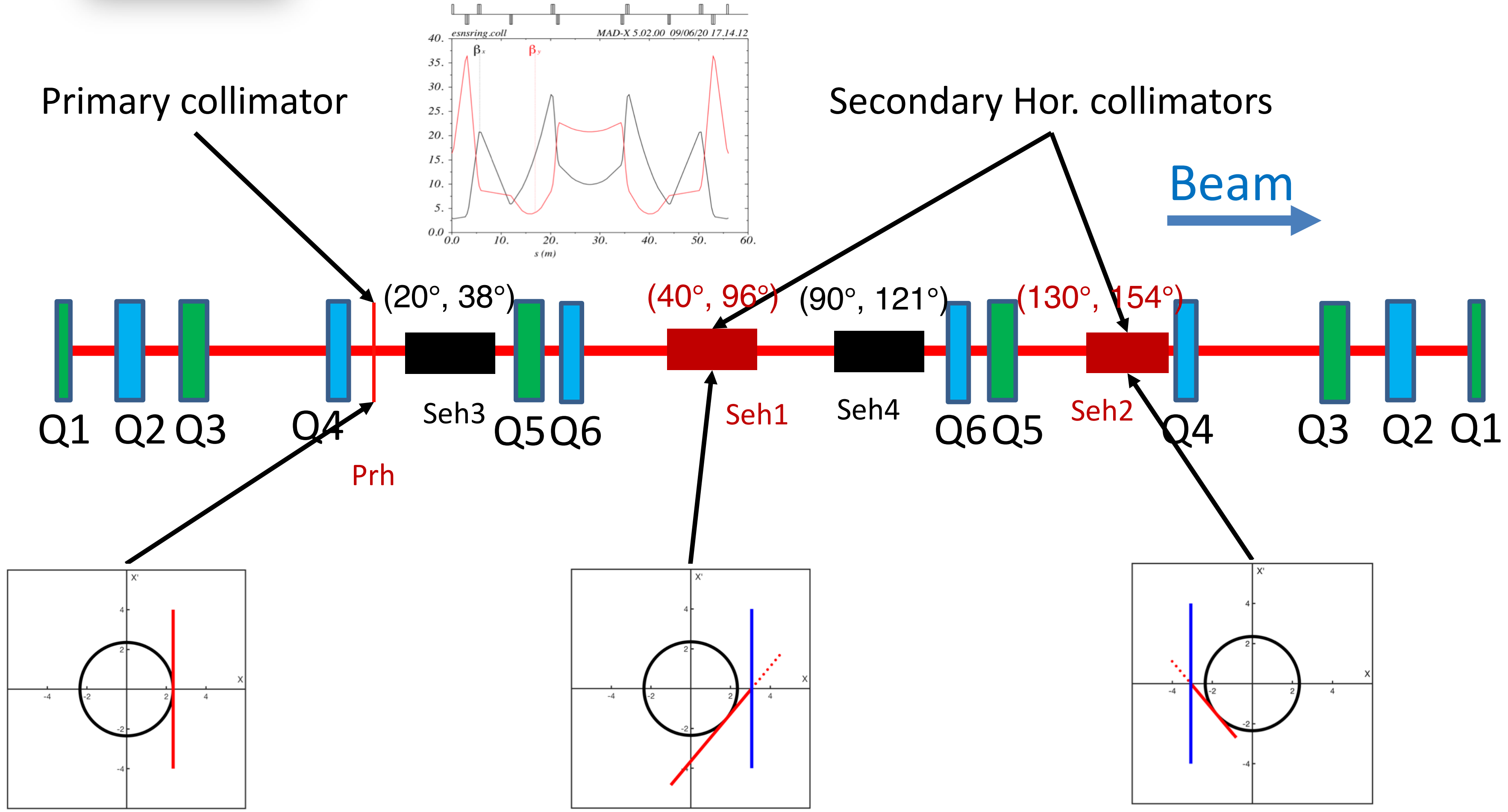
- To get maximum collimation efficiency, optimal phase advance between primary and secondary collimators can be calculated:

$$\mu_{\text{opt}} = \arccos\left(\frac{n_{\text{prim}}}{n_{\text{sec}}}\right)$$

- Secondary collimators that are located at μ_{opt} and $\pi - \mu_{\text{opt}}$ will intercept maximal number of the scattered particles
- The studies aim to evaluate the efficiency of two-stage collimation system for ESSnuSB accumulator
  - Fraction of particles lost on collimators when they pass through primary collimators
- PyORBIT are used to perform the numerical simulations of beam collimation
  - Thanks to the help from Sarah Cousineau (SNS)

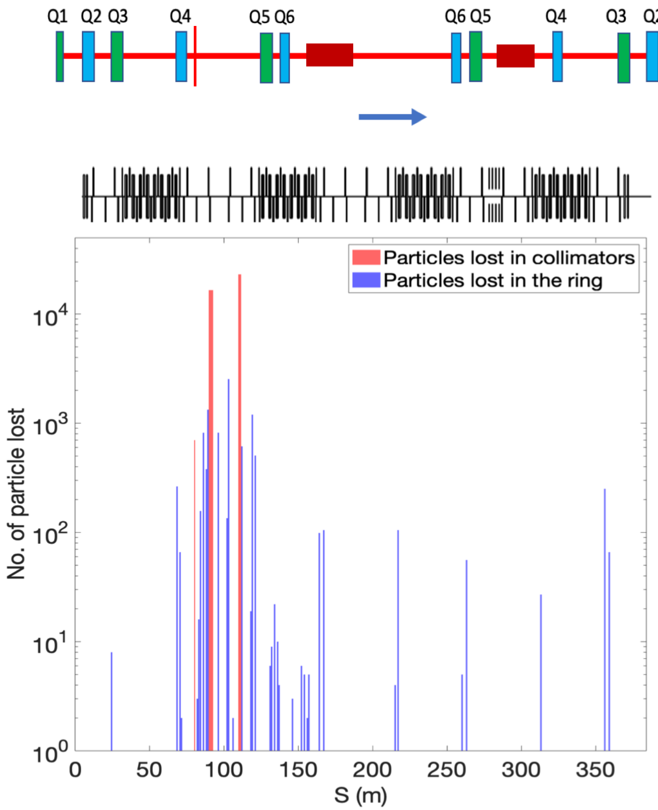


Location of the horizontal collimators

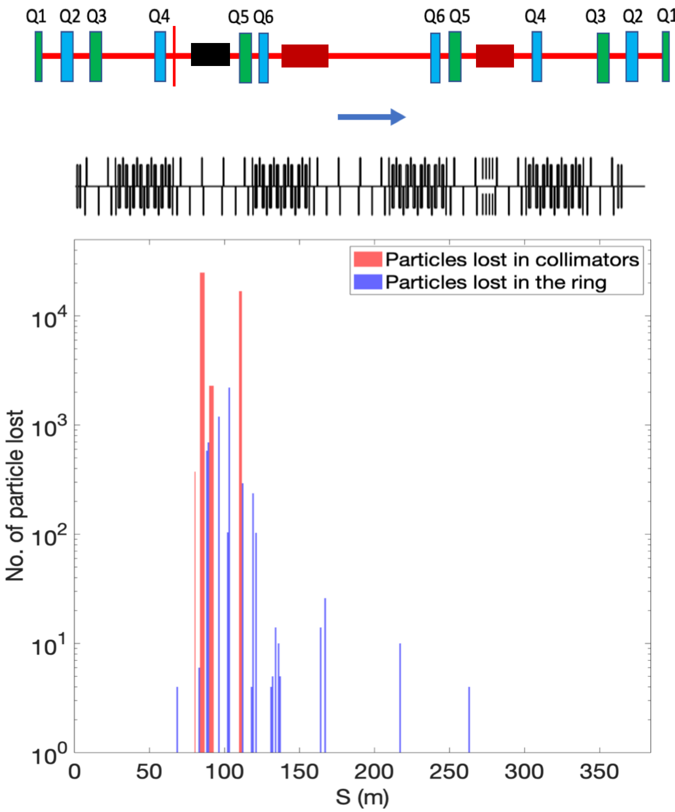


Ring Acceptance	200 pi mm mrad
Pri. Coll. Acceptance	70 pi mm mrad
Sec. Coll. Acceptance	120 pi mm mrad
Pri. Coll. length	1 mm
Sec. Coll. length(Seh1~4)	2m/1.8m/3m/2m
Pri. Material	Carbon
Sec. Material	Tungstun

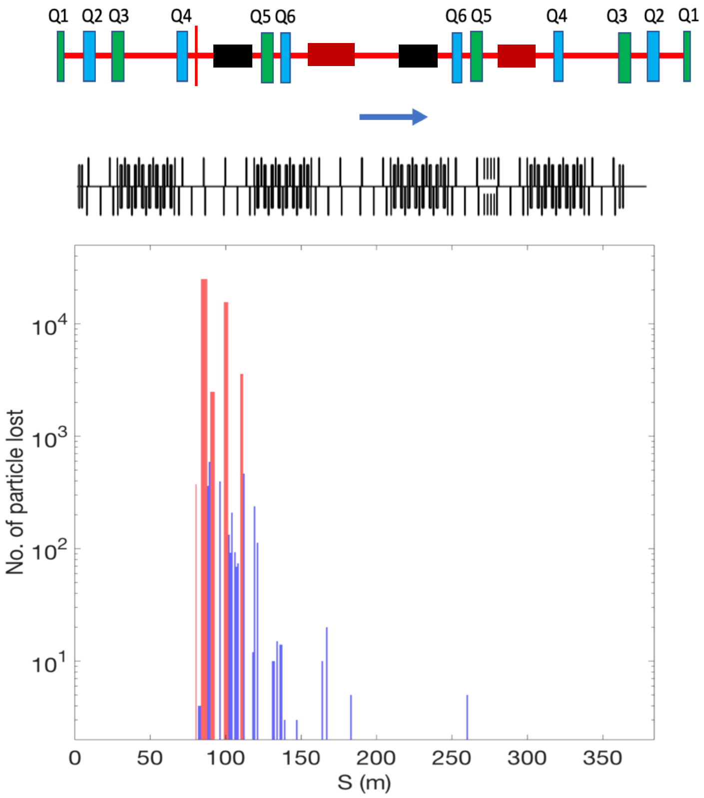
Beam loss map with different collimator settings



Coll. Efficiency: 80%



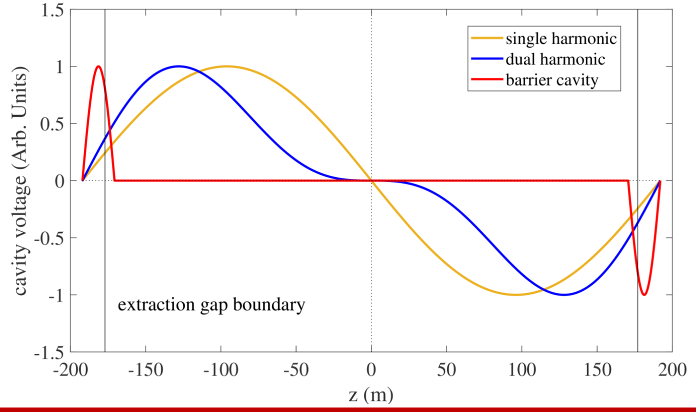
Coll. Efficiency: 89%

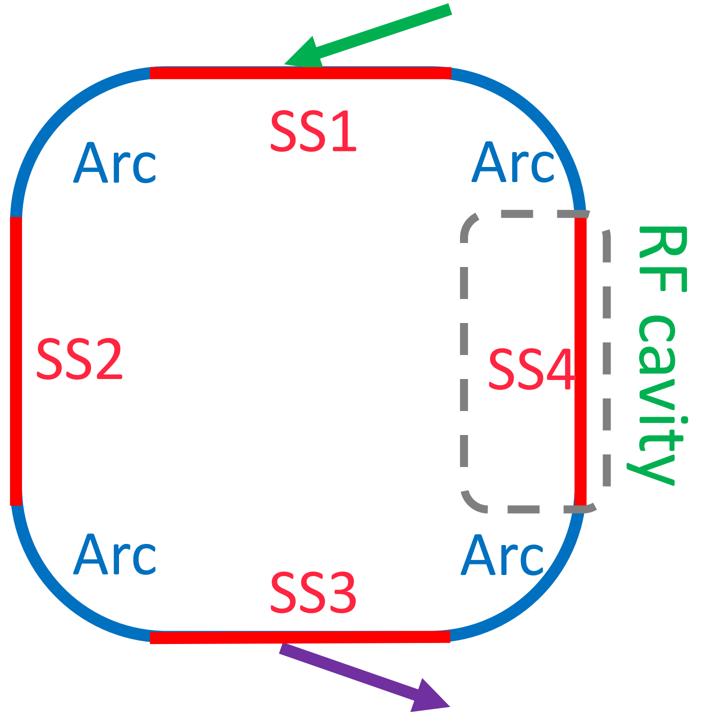


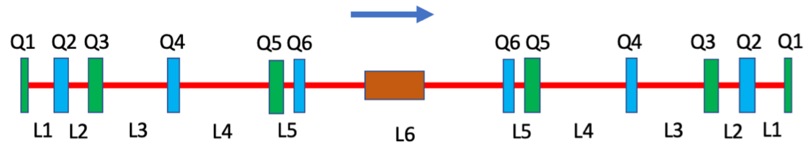
Coll. Efficiency: 94.5%

Longitudinal shaping: RF cavity

- RF cavity used to keep extraction gap clean during accumulation process, no acceleration
- Adopting different kinds of RF cavities (single harmonic, dual-harmonic, and barrier RF cavities) to trap the beam
- Single- or dual- harmonic RF cavity would increase energy spread to more than 1%, lead to more than 0.1 chromaticity-induced tune shift
- Barrier RF cavity only affects head and tail particles to keep the extraction gap clean



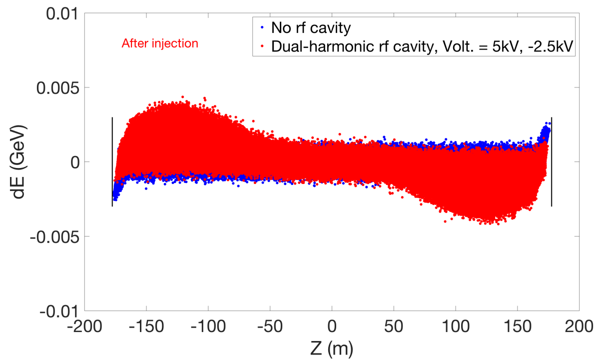




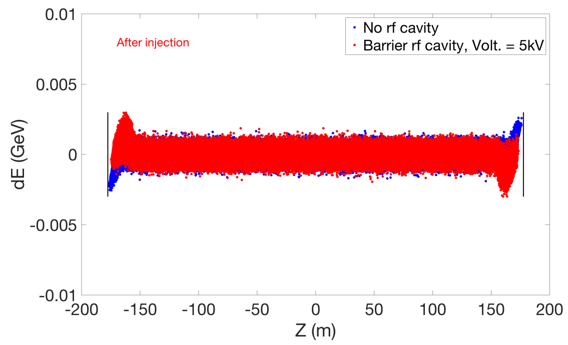
Longitudinal beam distribution with RF cavity

Point 1: Keep extraction gap clean during the whole accumulation process

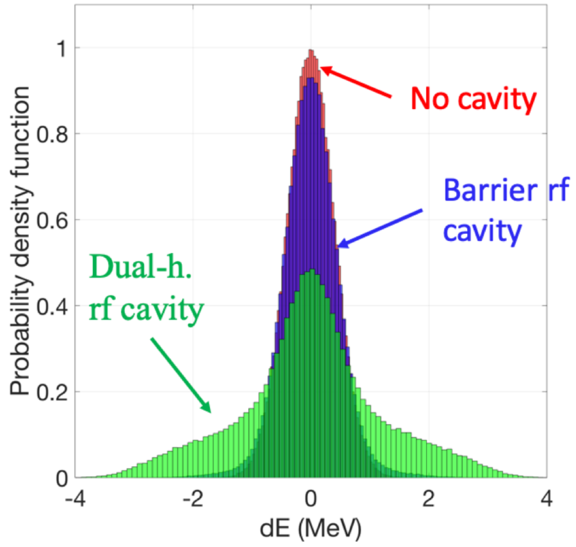
Point 2: Minimize the energy spread



Point 1: small risk to leak
Point 2: excellent (~ ±0.2%)



Point 1: excellent
Point 2: excellent (~ ±0.15%)



- Beam is quite stiff
- Particle leakage to the gap would be possible without RF cavity
- Small leakage risk and small energy spread if dual harmonic RF cavity with low voltage (~5kV)
- Very small leakage risk and very small energy spread if barrier RF cavity implemented
- Very small energy spread may cause longitudinal instability: Keil-Schnell longitudinal instability criterion can give us a threshold of longitudinal instability, but more involved simulation with a typical impedance model is needed to evaluate the possible issue

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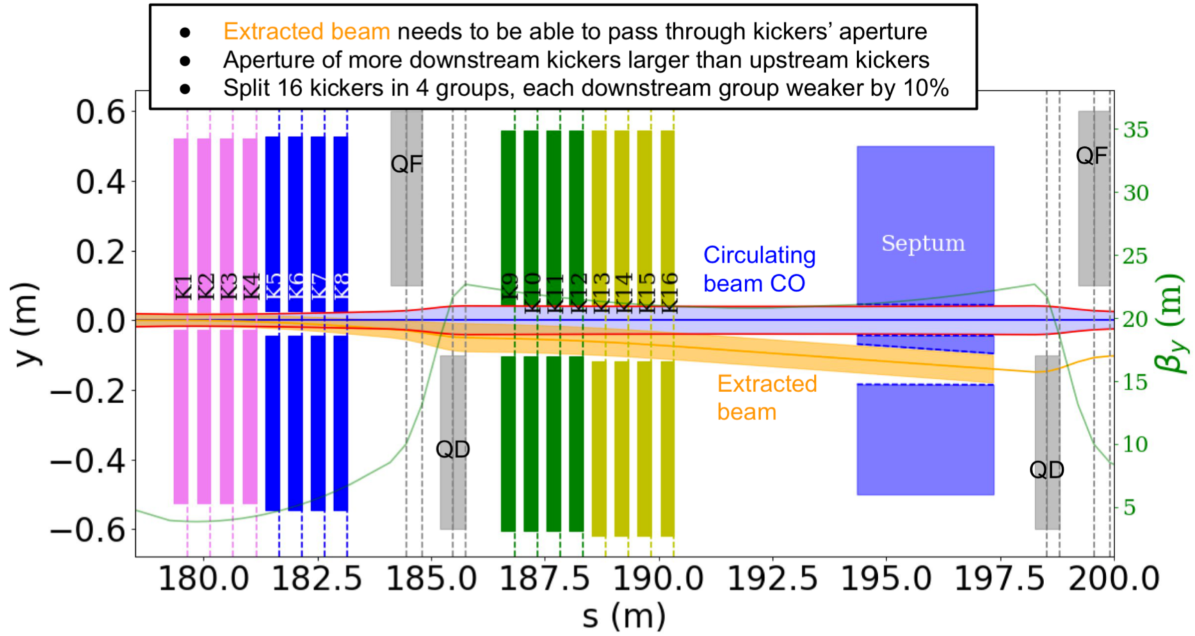
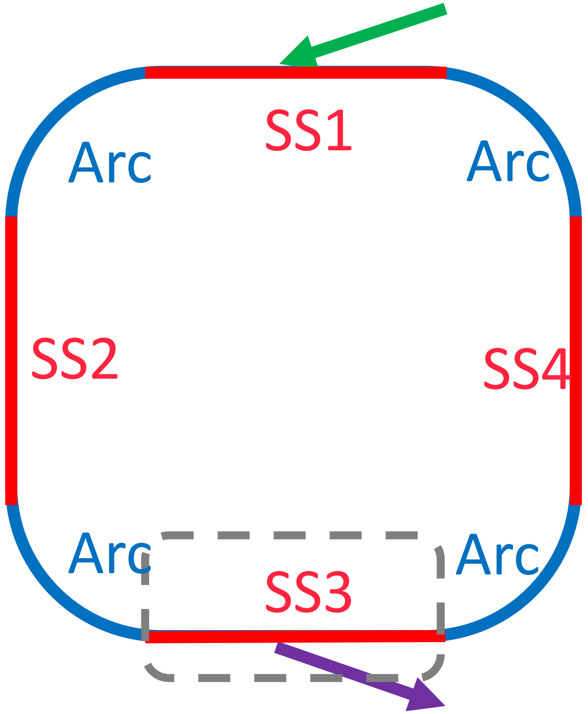
Beam extraction

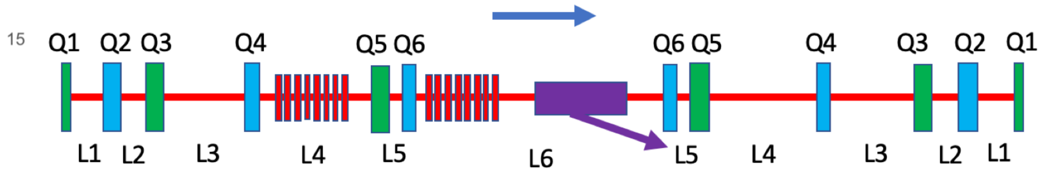
The fast kickers kick the beam vertically downwards into the Lambertson septum magnet, and the septum horizontally deflects the beam into the ring-to-target beam transport line.



Kicker aperture includes 5 mm margin on the top, and 5 mm on the bottom



Beam extraction



Androula Alekou

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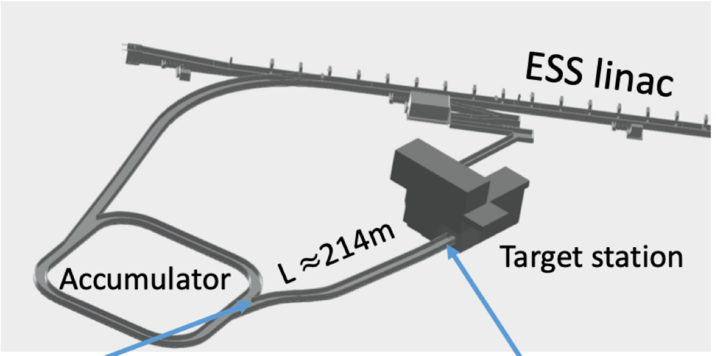
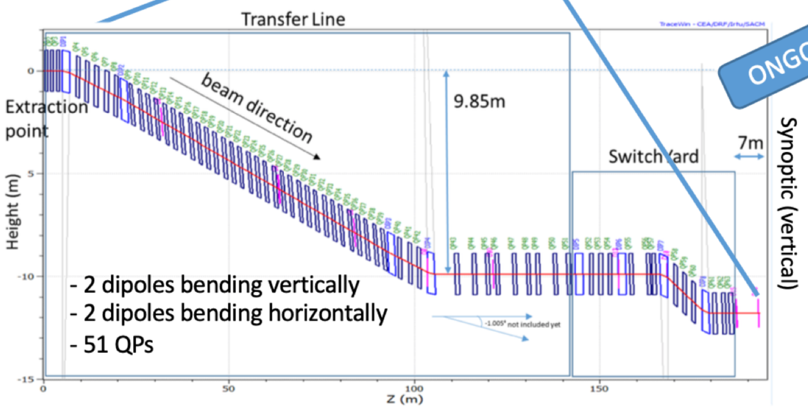
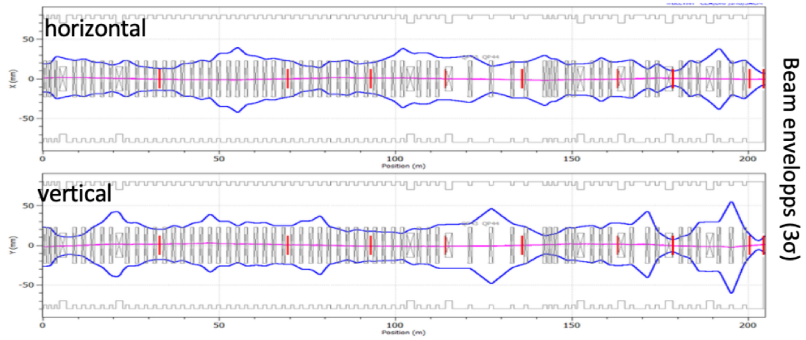
Ring to Target Station TL







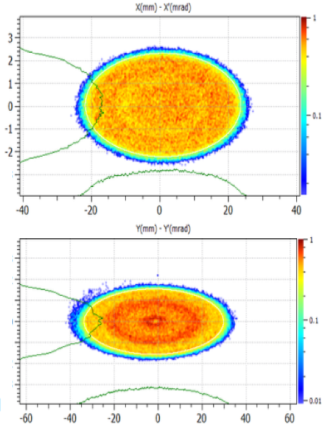
Beam input

X-X'
Emit [rms] = 45.3707 Pi.mm.mrad [Norm.]
Emit [95.81%] = 181.4830 Pi.mm.mrad [Norm.]
Beta = 9.9952 mm/Pi.mrad
Alpha = -0.0005

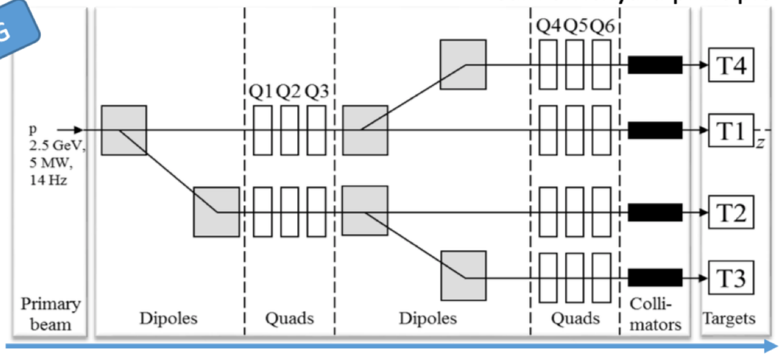
Y-Y'
Emit [rms] = 43.4780 Pi.mm.mrad [Norm.]
Emit [93.51%] = 173.9119 Pi.mm.mrad [Norm.]
Beta = 20.3566 mm/Pi.mrad
Alpha = -0.0032

Beta = 0.962044465 Gamma = 3.664443409
Mo = 938.27202900 MeV

4D (X-X'-Y-Y')
E [rms] = 1972.4439631603 (Pi.mm.mrad) ² [Norm.]

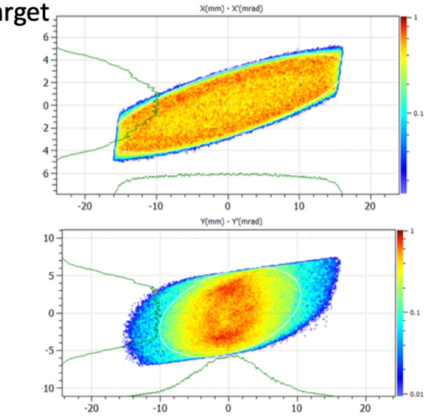


Beam swichyard principle



60-65m long

Beam at Target



Xmax = Ymax ≃15mm

Elian Bouquerel

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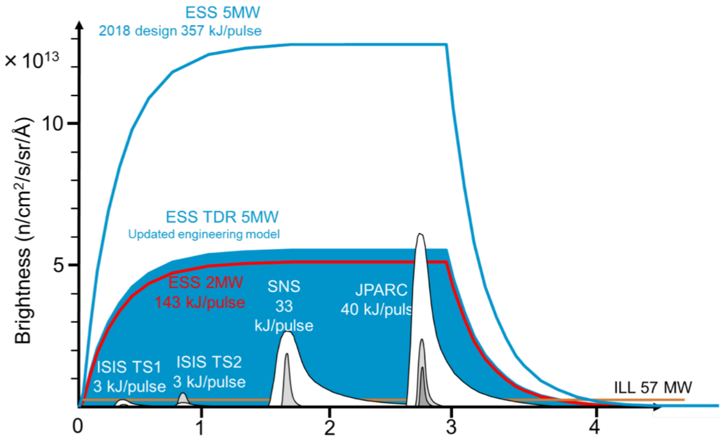
Slow extraction



Björn Gålnander

- Synergy: Short neutron pulses with high peak brightness for neutron spallation scattering community. See e.g. K. Anderson, High Intensity Workshop, Uppsala, 2020 *presentation*.
- Problem: Fast extraction of ~1 μs leads to high peak power, ~$3 \cdot 10^{11}$ W, (357 kJ per pulse) leading to excessive thermal and mechanical stress in the spallation target.
- Since the neutron moderation time for 5 Å neutrons is about 200 μs and will smear out the neutron pulse, a longer pulse of about 50-100 μs has small effect on neutron pulse with, but will reduce the peak power.
  - 357 kJ extracted at 50 μs or
  - 4 pulses of 50 μs about 750 us apart, each pulse 89 kJ.
- Slow extraction from the accumulator ring needs R&D to study the feasibility and possible impact on neutrino production.
  - Probably fast resonant extraction using half-integer resonance for this time scale.
- Losses are a problem, even with 99.5% efficiency achieved at J-PARC means 25 kW at 5 MW average power.
- High activation leads to problems with hands-on maintenance of e.g. electrostatic septum.

Summary

Where we are now:

- A well-designed lattice
- Beam painting to quite uniform distribution with 100% emittance ~60 π mm mrad
- Space charge tune shift: <0.05, very small
- Extraction gap can be kept clean
- Foil temperature issues can be mitigated in several ways
- Basic design of collimation system
- A new designed switchyard which has very small beam losses

Work in progress:

- Optimization of beam collimation system
- Chromaticity correction
- Transfer line design
- Beam dump design

Backup slides

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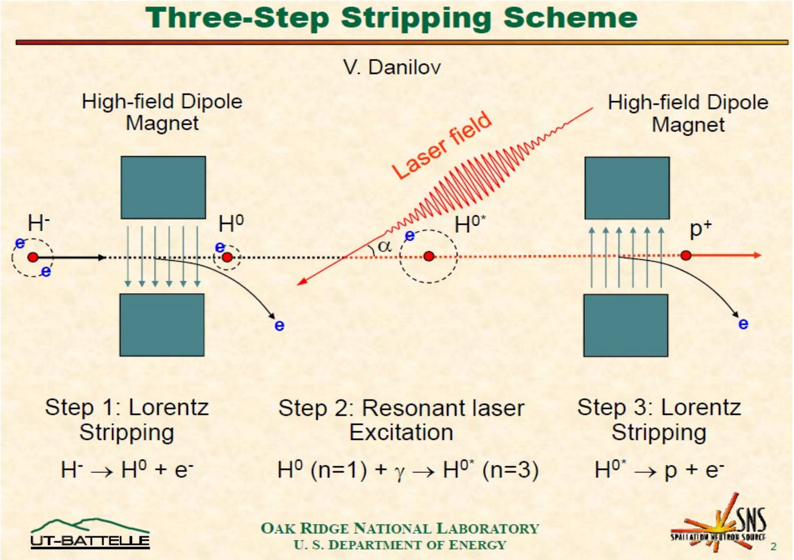
Laser stripping

V. Danilov, S. Cousineau

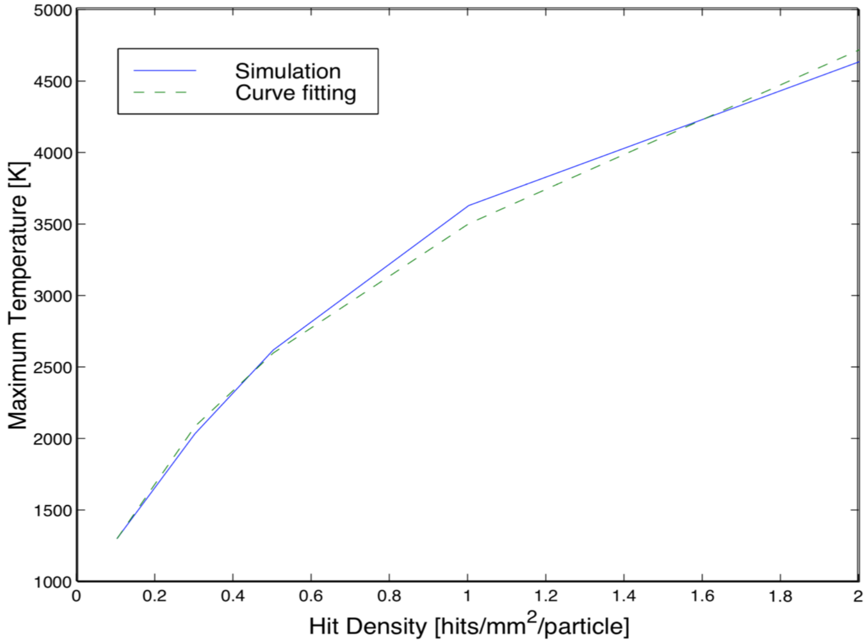
- A very promising alternative method for charge-exchange injection
- First demonstration of laser-assisted stripping (>90%) for a 6 ns, 1 GeV H^- beam using a 10 MW UV-laser at SNS in 2006
- First demonstration of laser-assisted stripping (95%-98%) for microsecond duration (10 us) H^- beams at SNS in 2016, by reducing the required average laser power
- Average laser power is the main limitation for H^- laser assisted charge exchange
- New scheme at SNS: sequential excitation scheme for laser stripping



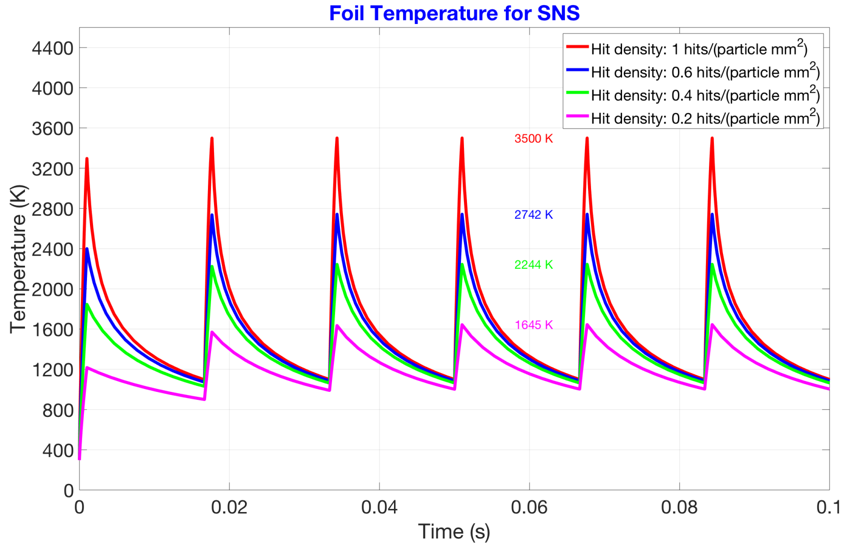
V. Danilov et al., PRST-AB 10, 053501 (2007)

Sarah Cousineau et al., PRL 118, 074801 (2017)

Temperature calculation code benchmark with SNS results



J. Beebe-Wang et.al., BNL, proceedings of 2001 PAC Chicago, USA



Hits density (hits/(p mm^2))	SNS results (K)	Code results (K)
0.2	~1660	1645
0.4	~2300	2244
0.6	~2750	2742
1.0	~3500	3500

Lattice parameters compared with SNS

Parameter	ESSnuSB	SNS1.4MW
Circumference (m)	384	220
Average radius (m)	61	35
Inj./Ext. Energy (GeV)	2.5/2.5	1/1
Repetition rate (Hz)	14	60
Ring dipole field (T)	1.3	0.74
Magnetic rigidity, Bρ (T m)	11	5.7
Max beta hor./ver. (m)	29/35	20/13
Hor./Ver. Tune	8.24/8.31	6.3/5.8
Transition energy, γ_T	5.82	4.95
Hor./Ver. natural chromaticity	-11.2/-12.4	-7.5/-6.3
Number of superperiods	4	4