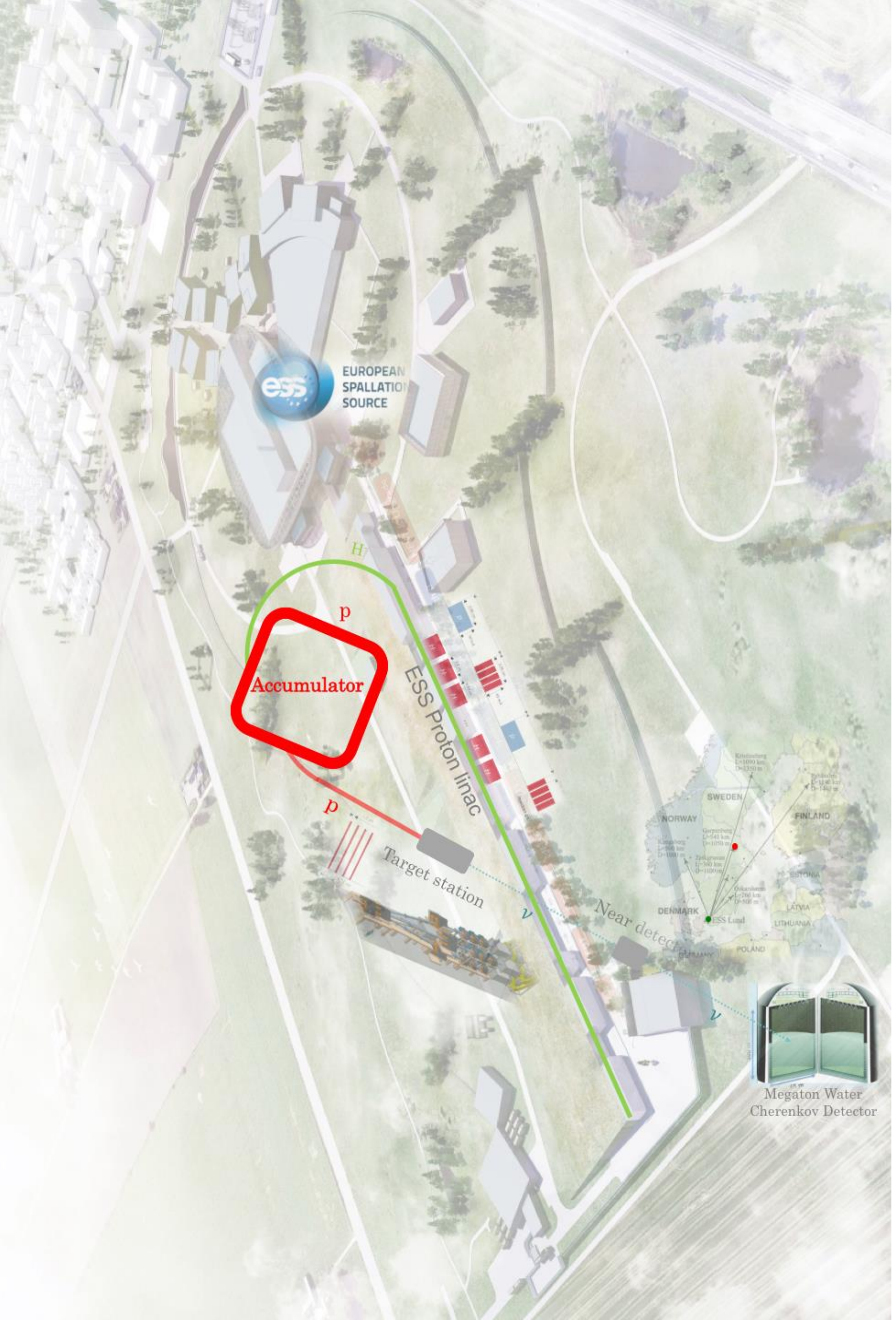


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UNIVERSITET

Funded by the Horizon 2020 Framework Programme of the European Union

# The design of the ESSnuSB accumulator and its synergies with the different proposals presented

**Ye Zou, Maja Olvegård, Uppsala University,**

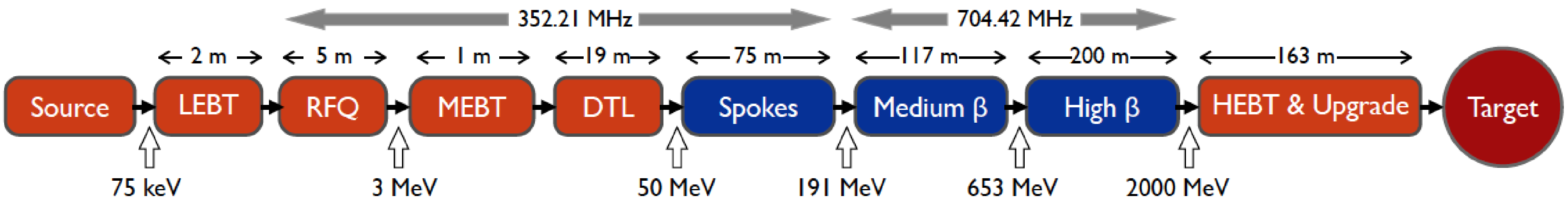
**on behalf of the ESSnuSB WG3**

ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

EuroNuNet

# The European Spallation Source




| Parameter | Value |
|---|---|
| Ion species | Proton |
| Average beam power | 5 MW |
| Peak beam power | 125 MW |
| Ion kinetic energy | 2 GeV |
| Average macro pulse current | 62.5 mA |
| Average macro pulse length | 2.86 ms |
| Pulse repetition rate | 14 Hz |
| Duty cycle | 4% |

> $2.7 \times 10^{23}$ p.o.t/year by 2023

# Add a neutrino facility at the ESS

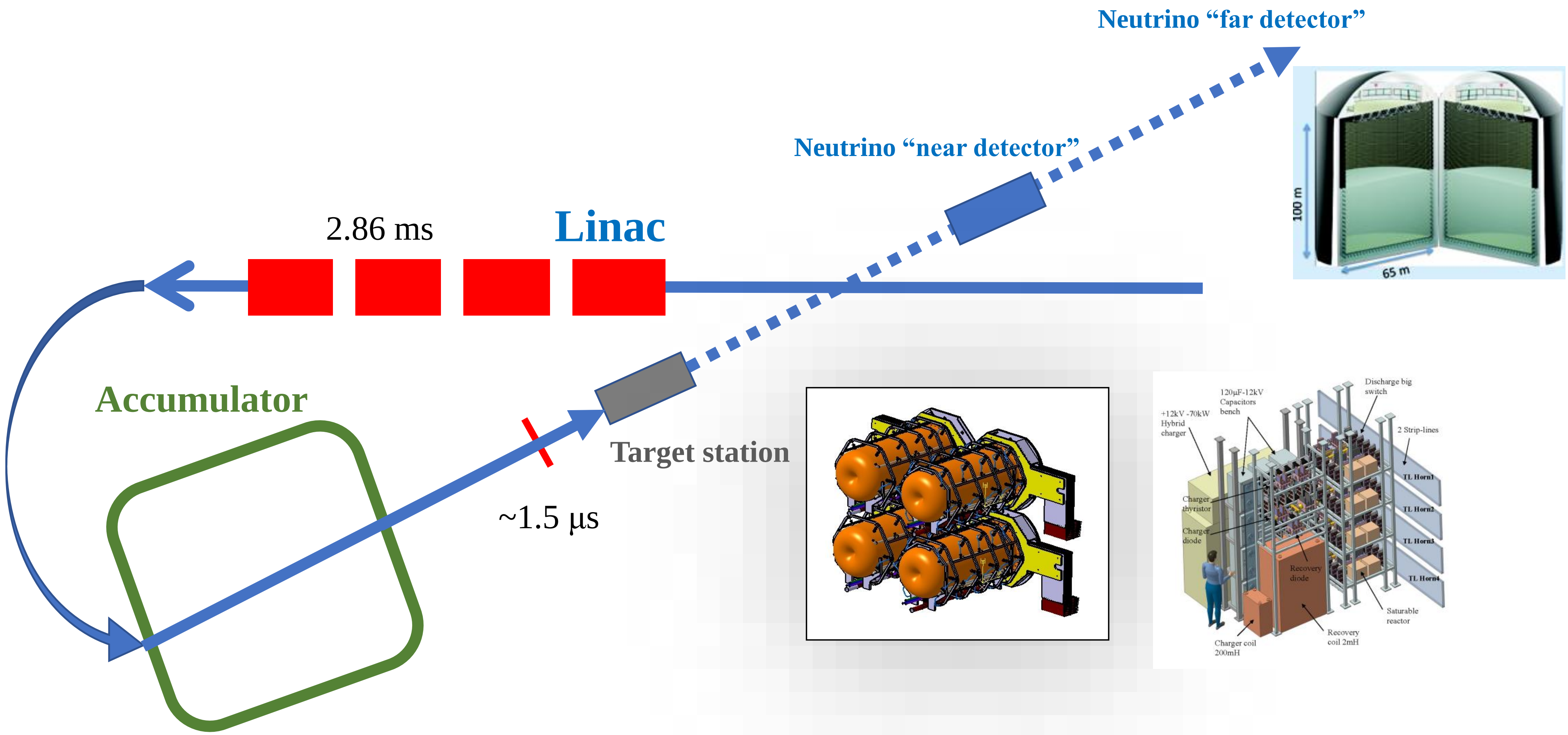
## *Why?*

Because of the uniquely high power of the ESS linac we will have the opportunity to measure **with high precision** the neutrino CP-violating angle at the 2nd oscillation maximum

## *How?*

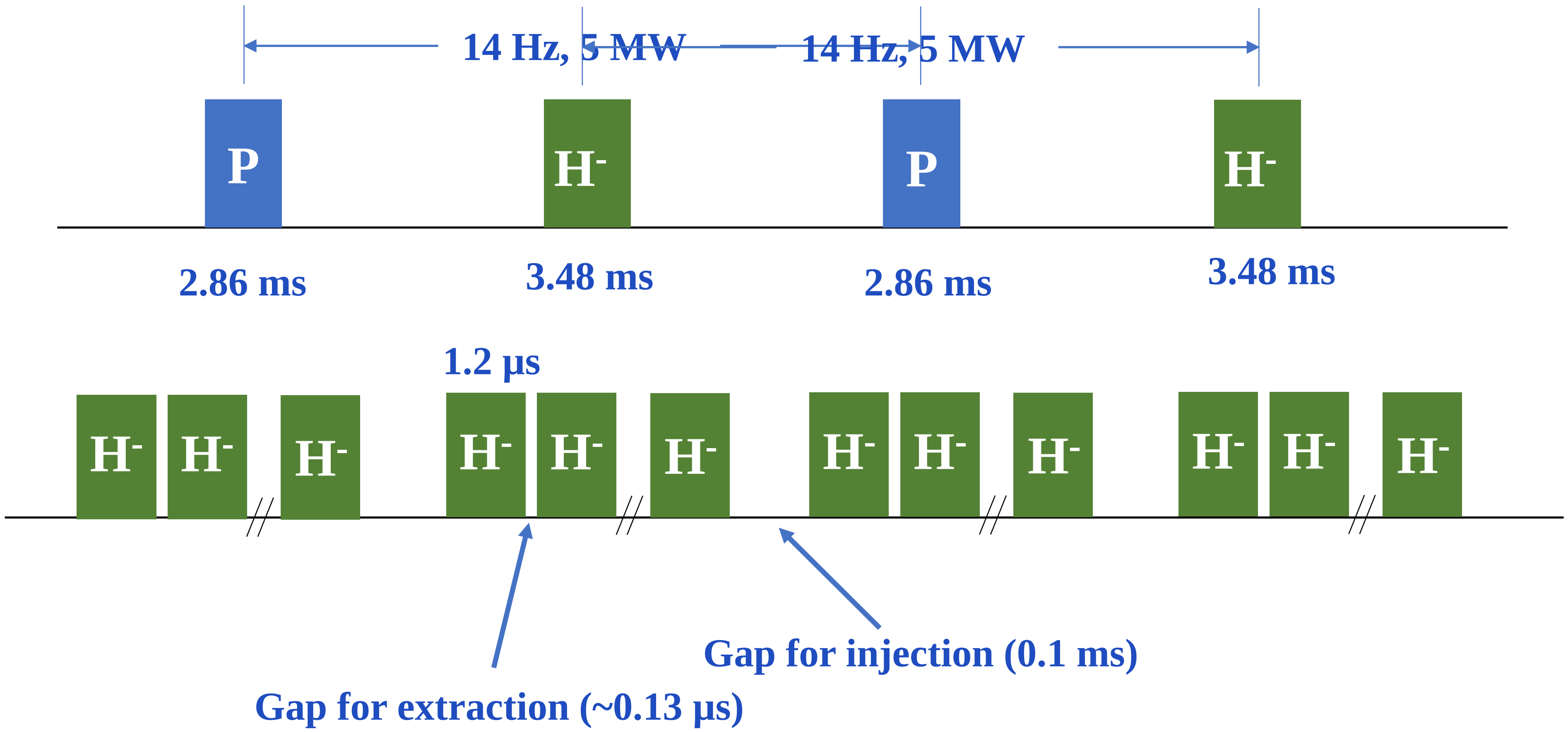
- ❑ Linac modifications (double the rate (14 Hz → 28 Hz), duty cycle (4% → 8%), average beam power (5 MW → 10 MW)) (see Björn Gålnander’s talk)
- ❑ Neutrino target station (see Eric Baussan’s talk )
- ❑ Underground detectors (studied in LAGUNA)

# Accumulator

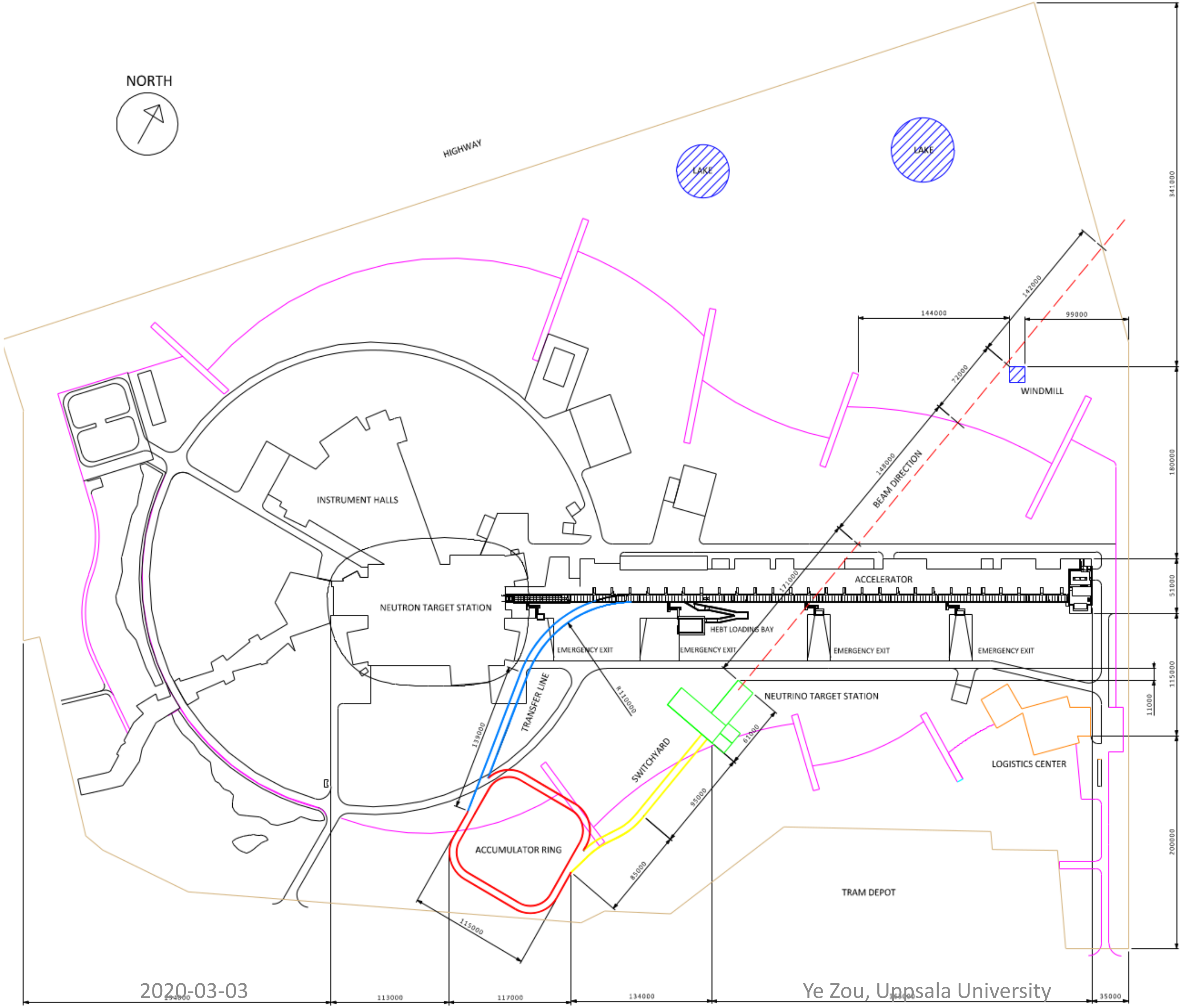



***Highly compress the pulse from the ESS linac in order to meet the target station requirements***

# Pulse from linac



# Transfer line



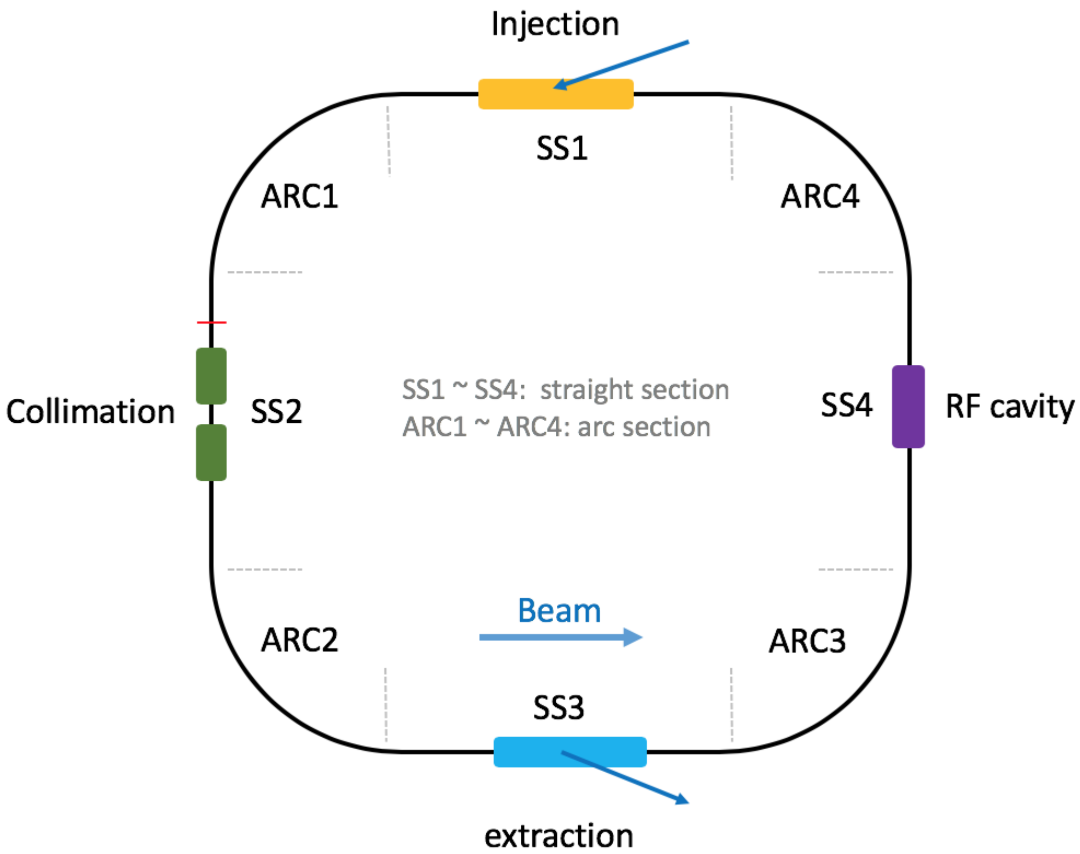

- Maximum magnetic field 0.15 T for 0.1 W/m loss due to Lorentz stripping.
- 2/3 of transfer line filled with dipoles yields a minimum total radius of 110 m.
- 2.5 GeV extraction not hit target building

Rasmus Johansson & Nick Gazis, ESS

# Accumulator design

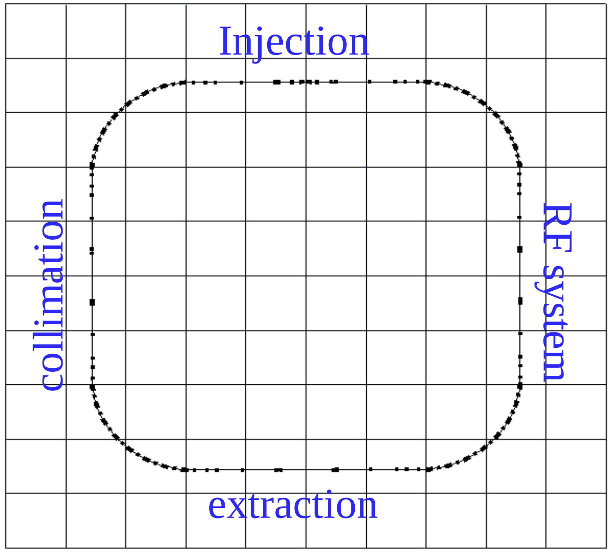
- Sub-pulse from Linac:
    - Energy: 2.5 GeV
    - Power: 1.25 MW
    - Current: 50 mA
    - Beam intensity: $2.23 \times 10^{14}$
- The circumference of the ring: ~ 400 m
- Injection turns: ~ 600
- Extraction gap: ~100 ns
- Un-Norm. 100% emittance: ~80 π mm mrad
- Total beam loss (1 W/m): $<10^{-4}$
- Collimation efficiency: 90%
- Space-charge tune shift: <0.05

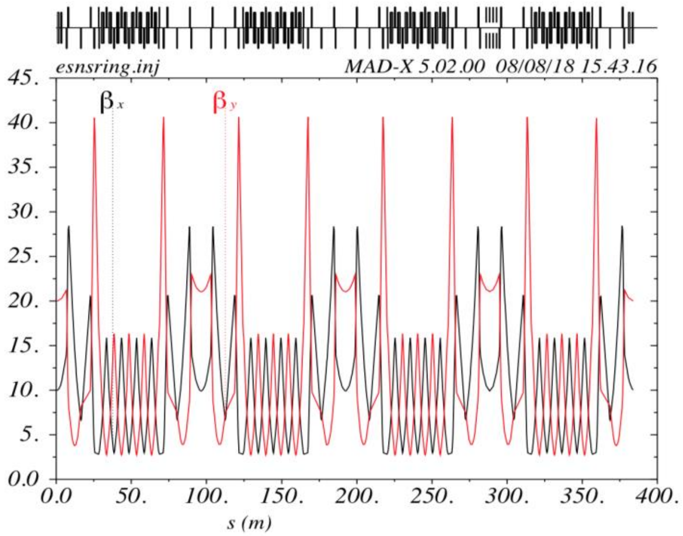
$$\Delta Q = -\frac{r_0 N}{2\pi E_{x,y}\beta^2\gamma^3 B f}$$




Uncontrolled beam loss usually comes from high space charge induced tune shift, beam injection, acceptance, instabilities…

# Lattice development




Developed by Horst Schonauer

- Inspired by the SNS accumulator ring which runs under similar conditions
- Long straight section (56 m) and enough phase advance for beam injection and collimation
- Fixed injection chicane (9 cm) and fast programmable bump for injection painting

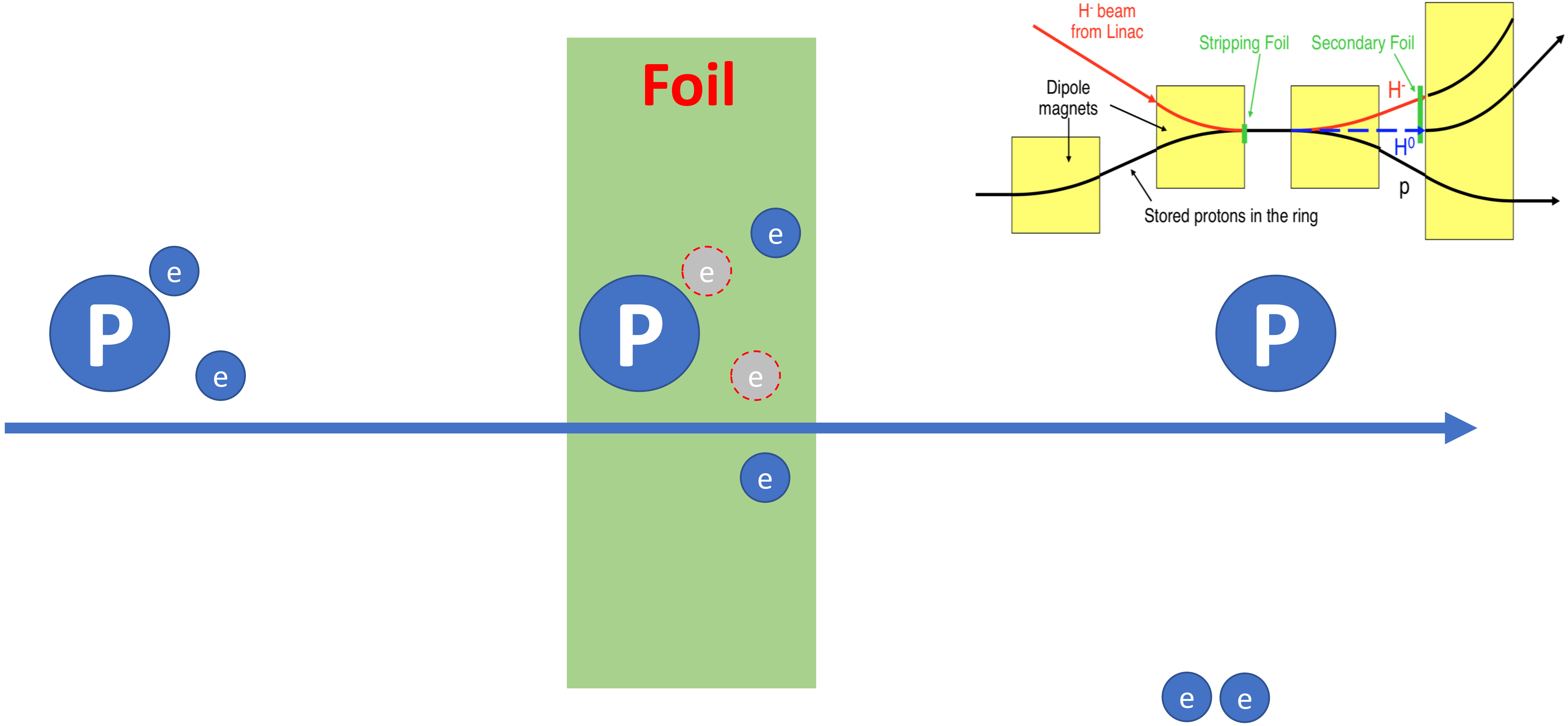
| Parameter | ESSnuSB | SNS1.4MW |
|---|---|---|
| Circumference (m) | 384 | 220 |
| Average radius (m) | 61 | 35 |
| Inj./Ext. Energy (GeV) | 2.5/2.5 | 1/1 |
| Repetition rate (Hz) | 14 | 60 |
| Ring dipole field (T) | 1.3 | 0.74 |
| Magnetic rigidity, B$\rho$ (T m) | 11 | 5.7 |
| Max beta hor./ver.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

# Beam injection

- Beam injection (proton or $H^-$ injection?)
  - Proton injection: Liouvillean, Beam loss on septum unavoidable if many turns injected, in particular with space charge effect
  - $H^-$ injection: Non-Liouvillean, proton can be overlaid on $H^-$ in phase space, very high beam intensity can be injected to the accumulator

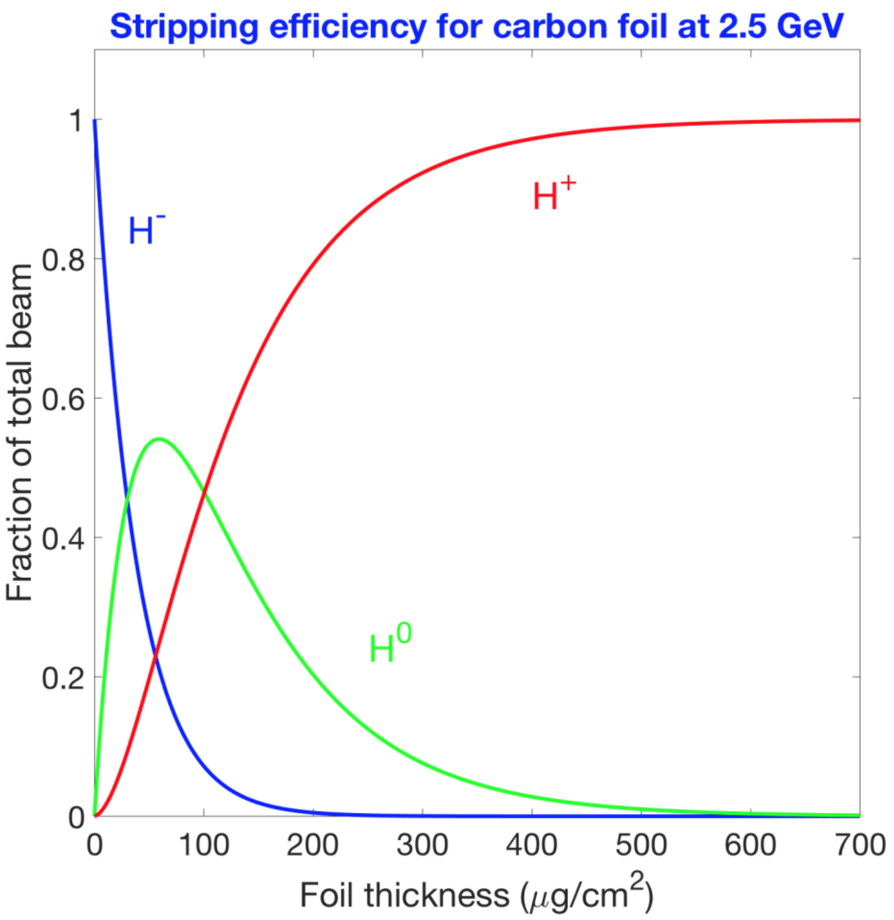
- $H^-$ injection (foil stripping or laser stripping?)
  - Foil stripping: used in similar proton synchrotrons or accumulators, straightforward, but very challenge for ESSnuSB
  - Laser stripping: a promising alternative method

# Foil stripping: very challenge



# Foil stripping: very challenge

- Stripping efficiency:
  - A function of foil material, foil thickness, foil density, beam species, and beam energy
  - For carbon foil, thickness is 500 μg/cm$^2$ if stripping efficiency required at least 99%
  - As the foil thickness increases, stripping efficiency increases, scattering increases, energy deposition in the foil increases
- Foil temperature:
  - can decrease the foil lifetime sharply when temperature exceeds 2000 K
  - Several methods adopted to mitigate the issue
- Foil scattering, cause residual radiation
- $H^{0*}$ (n=4, 5), should be considered carefully
- Stripped electrons, should be considered carefully

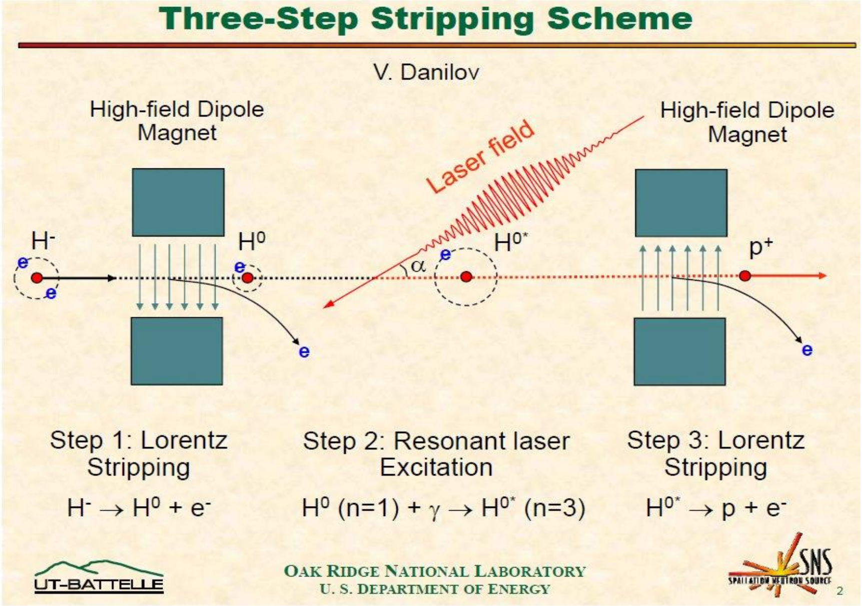



*H- stripping cross section scaled from [M.S. Gulley et al., Phys. Rev. A 53 (1996) 3201](#)*
*[W. Chou et al., Proceedings of PAC07, Albuquerque, New Mexico, USA, p1679](#)*

# 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



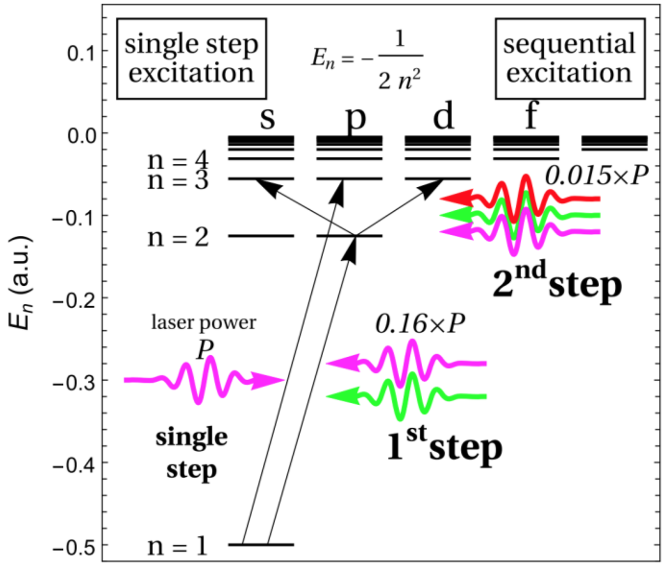

V. Danilov et al., PRST-AB 10, 053501 (2007)

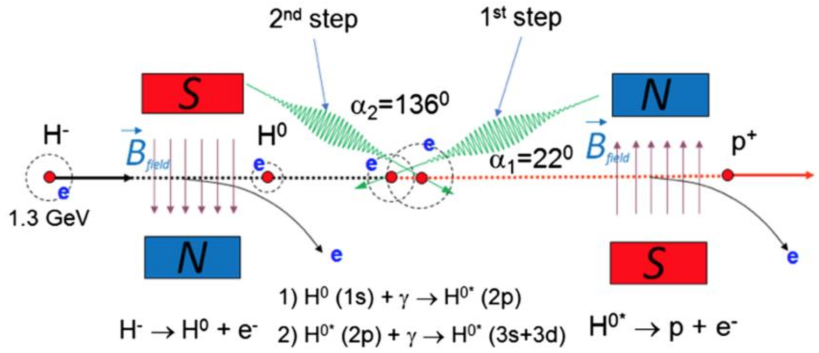
Sarah Cousineau et al., PRL 118, 074801 (2017)

# Sequential excitation scheme for laser stripping at SNS

Timofey Gorlov

- Two steps excitation in stead of one: excite the $H^0$ from the ground state to the 2nd state (1s → 2p), followed by excitation from the 2nd to the 3rd state (2p → 3d)
- Each step of the sequential excitation 1s → 2p and 2p → 3d requires smaller laser power
- Other alternative laser wavelengths, e.g. green laser would be possible.
- The available laser power drops dramatically as the wavelength gets shorter
- An order of magnitude in laser power savings by using the double excitation scheme
- The experimentally testing for this scheme is in process at SNS this year



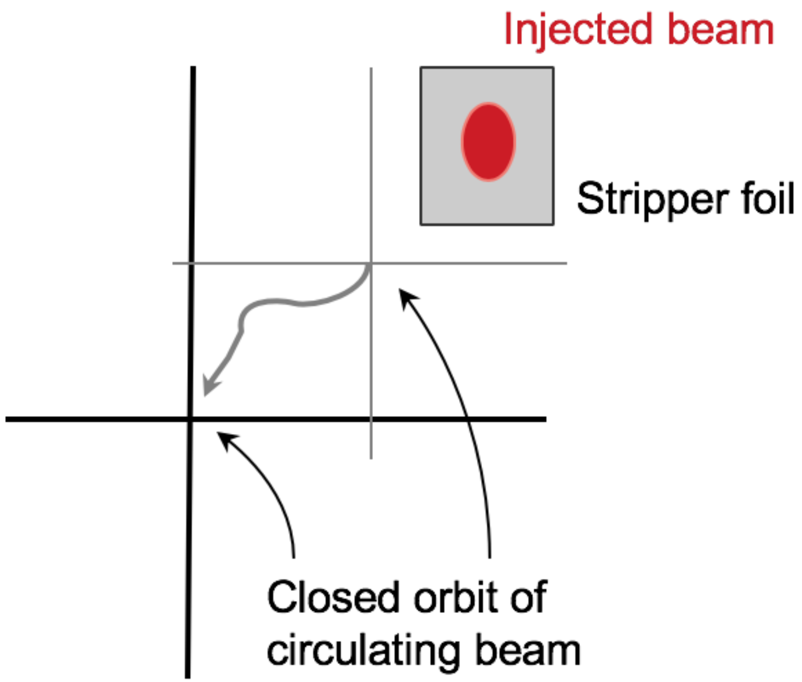



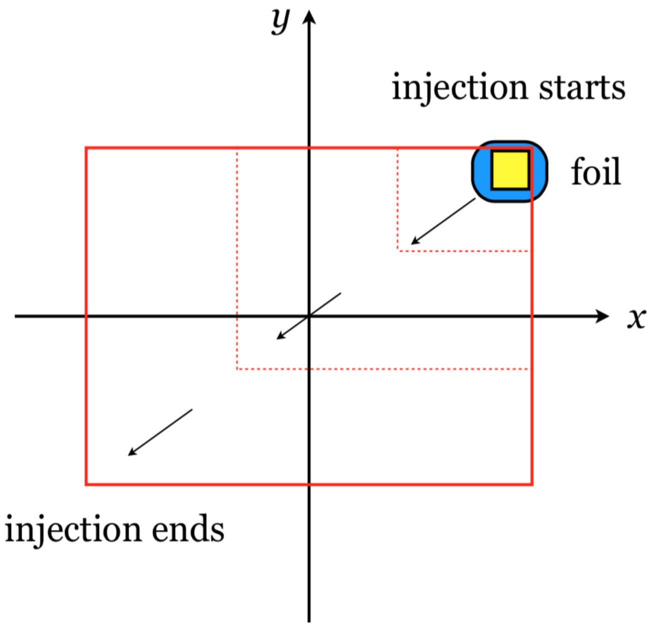

Timofey Gorlov et al., PRAB, 22, 121601 (2019)

# Painting

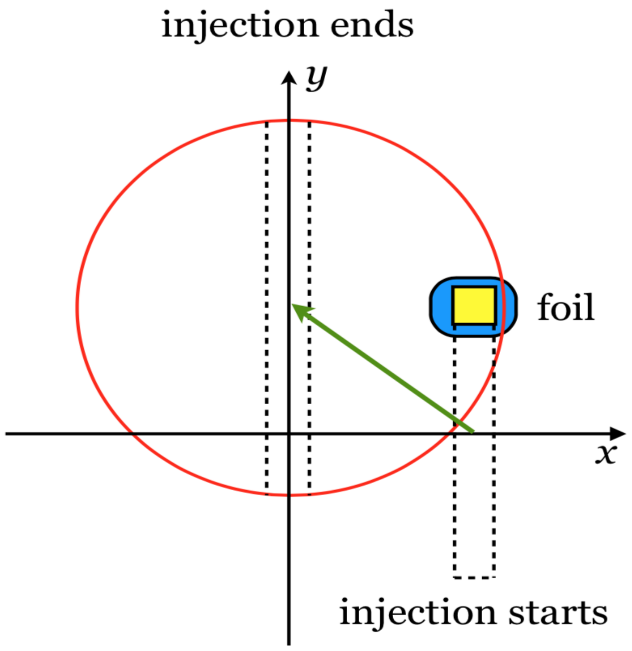
# Beam painting

- A good beam painting can reduce space charge effect, and mitigate peak foil temperature
- Correlated painting and anti-correlated painting



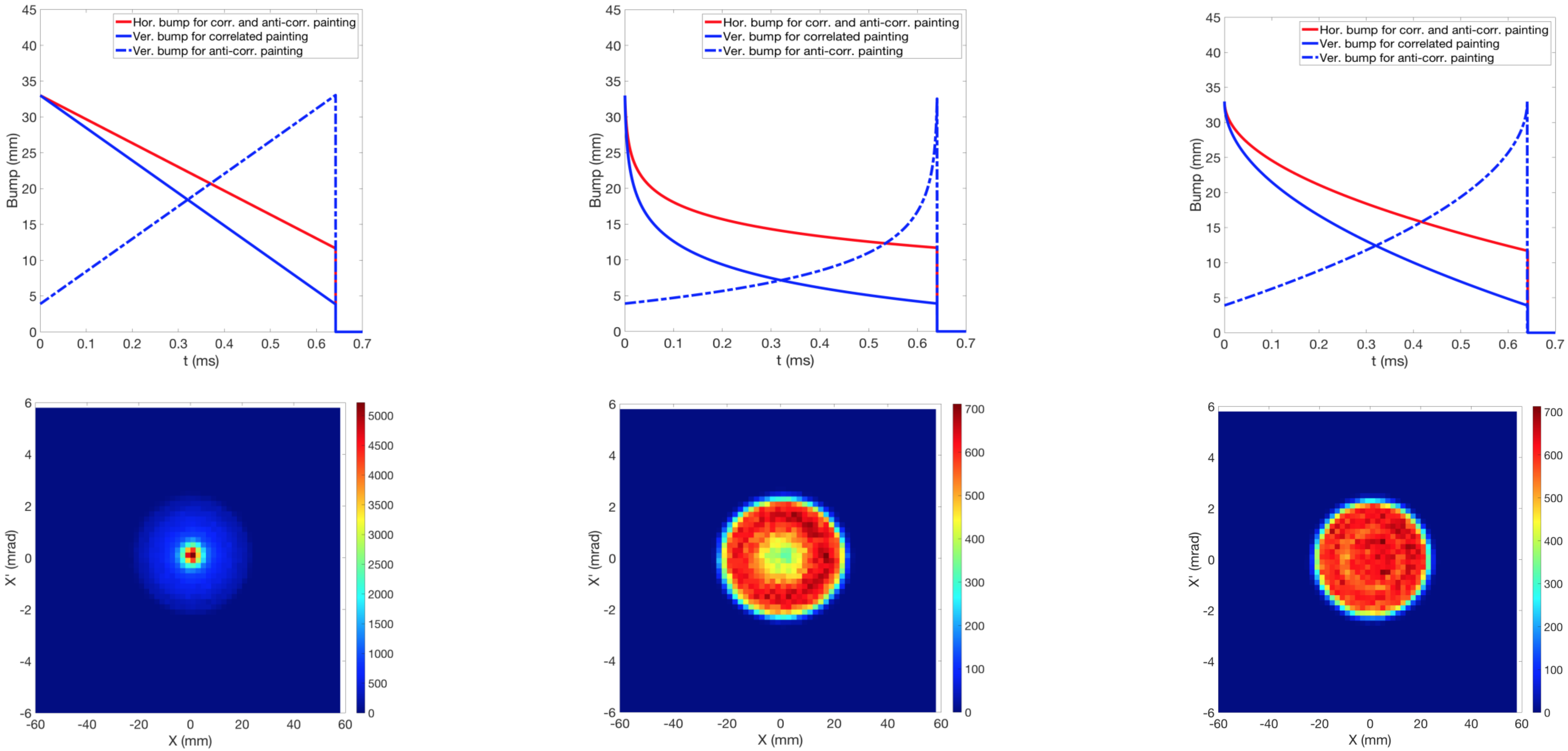

Correlated painting




Anti-correlated painting

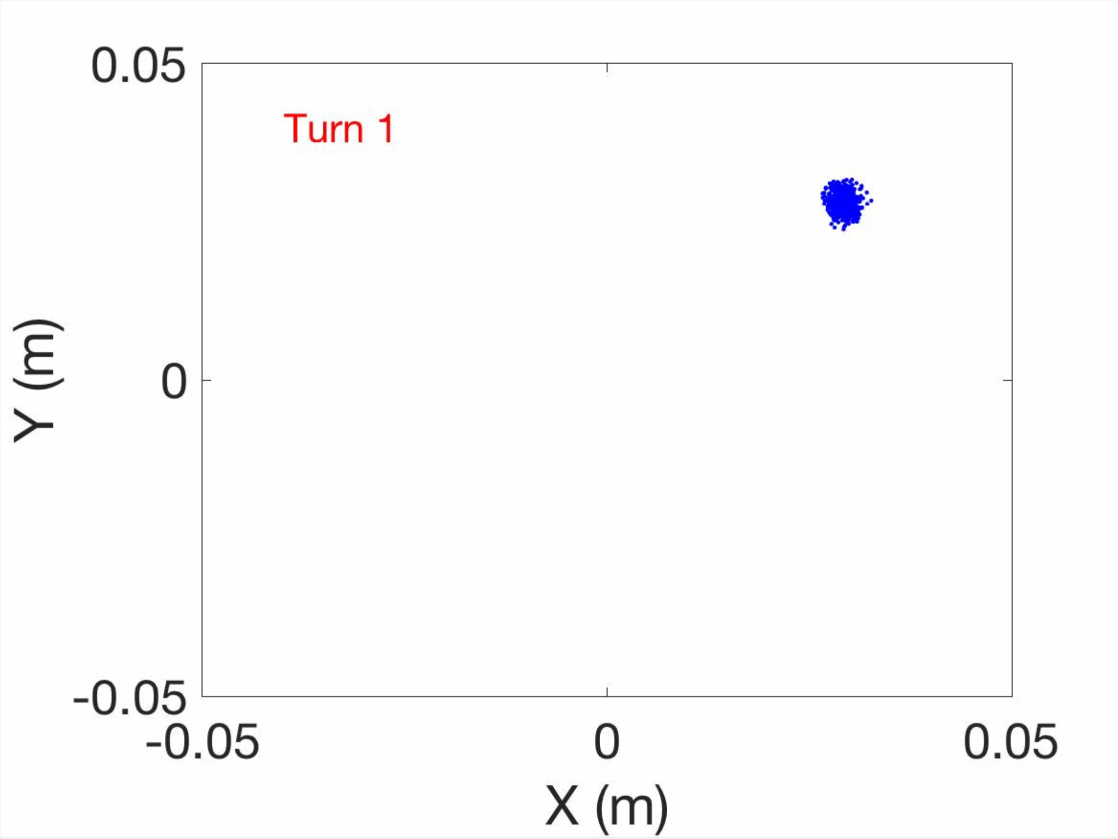
# How to make a “good” painting

- Optimize the painting process to get beam distribution that we need

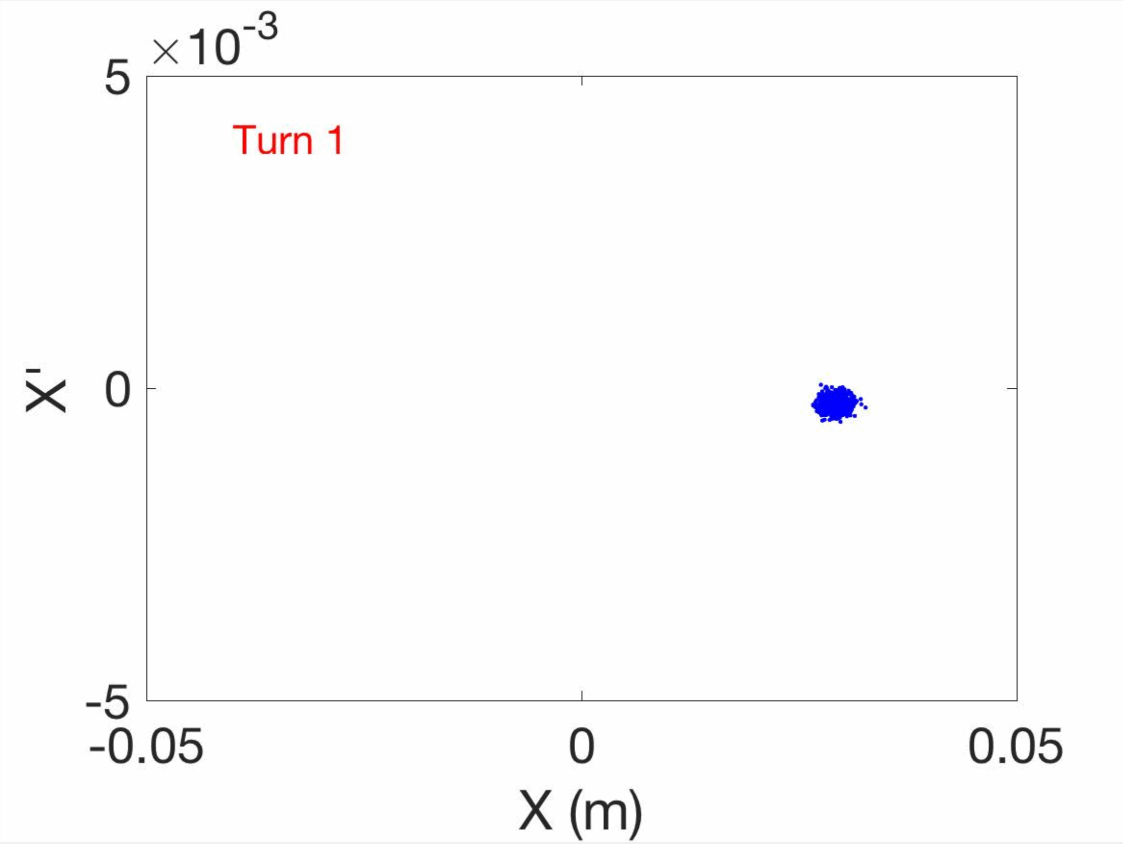


# An example of beam painting

**Painting in real space**

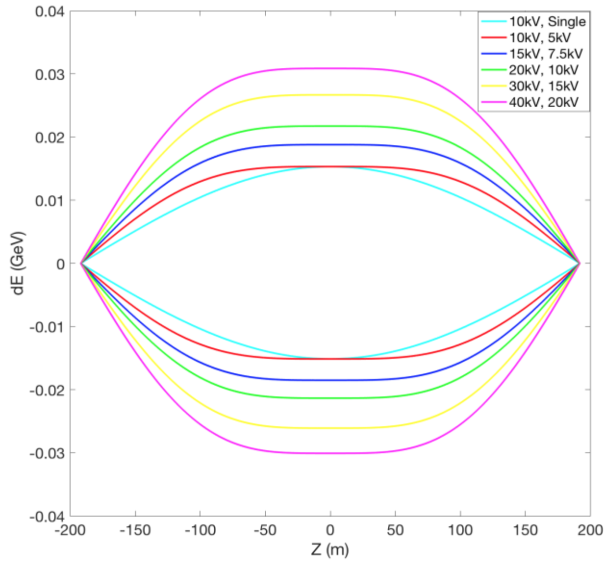



**Painting in phase space**

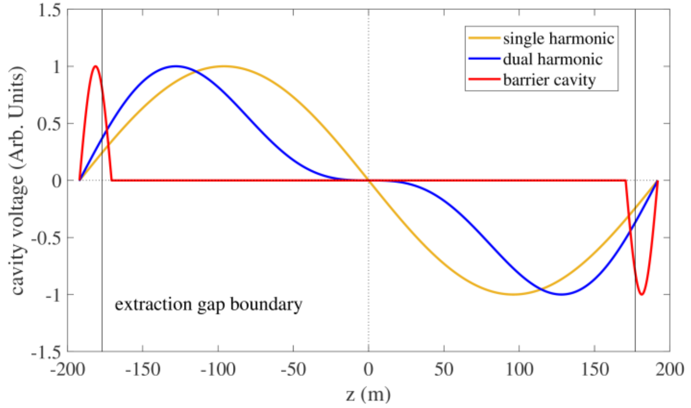


# Longitudinal shaping: RF cavity

- RF cavity used to keep extraction gap clean during accumulation process, no acceleration
- Utilizing different kind 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 affect head and tail particles to keep the extraction gap clean




Single and dual harmonic rf bucket




RF waveform

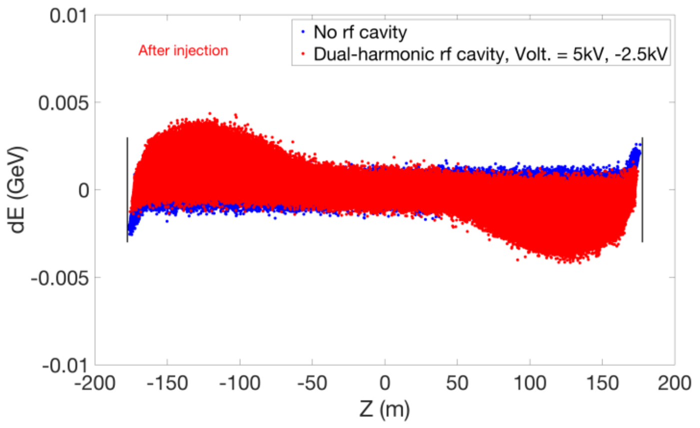
# Longitudinal beam distribution with RF cavity

**Two main points**

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

**Point 2: Minimize the energy spread**

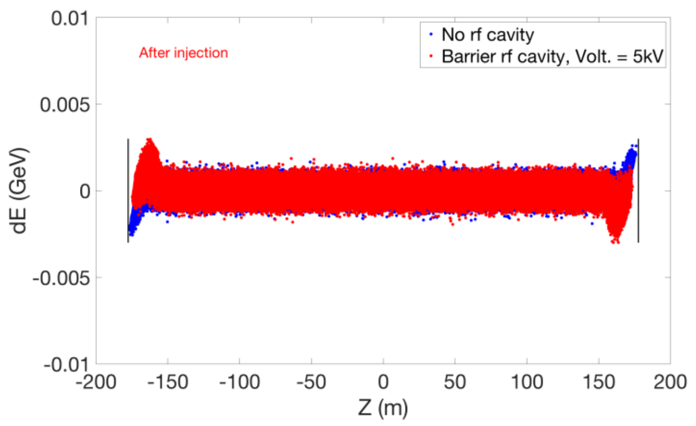
Dual Harmonic RF cavity (Low voltage, 5kV)




Point 1: small risk to leak

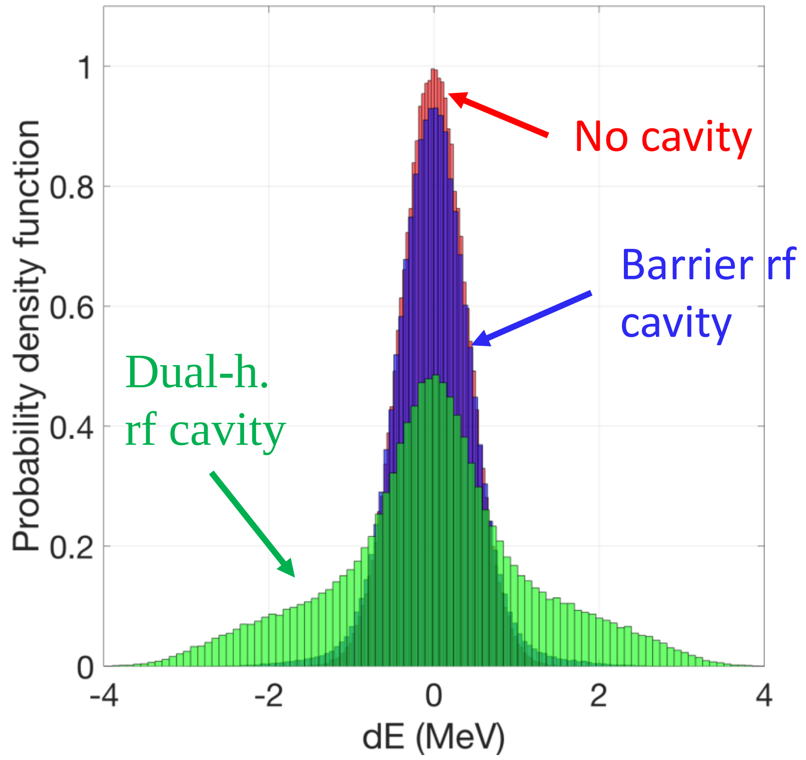
Point 2: excellent (~ ±0.2%)

Barrier RF cavity




Point 1: excellent

Point 2: excellent (~ ±0.15%)

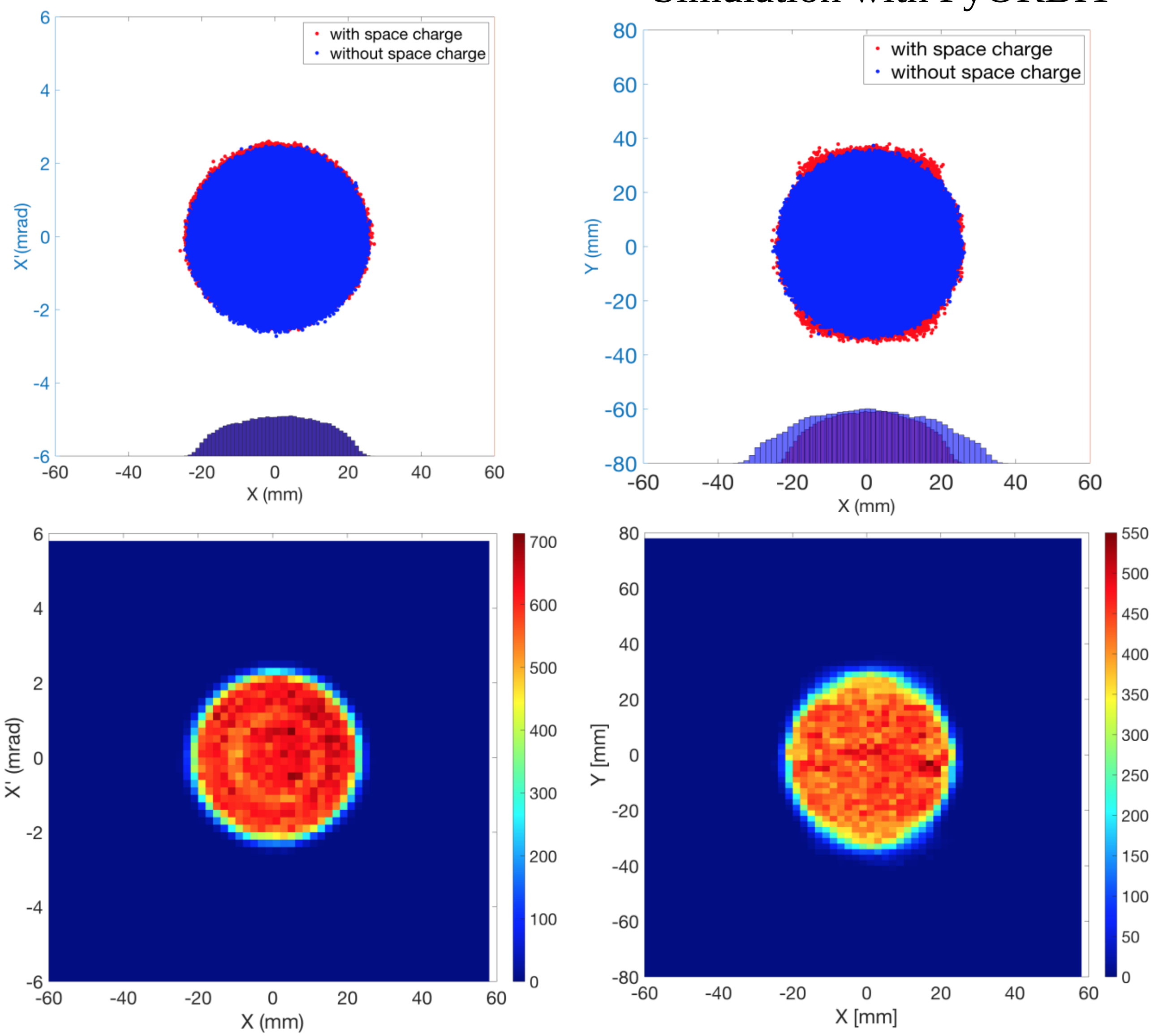



- Beam is quite stiff
- Particles leakage to the gap would be possible without RF cavity
- Small risk to leak and small energy spread if dual harmonic rf cavity with low voltage (~5kV)
- Very small risk to leak and very small energy spread if barrier rf cavity implemented

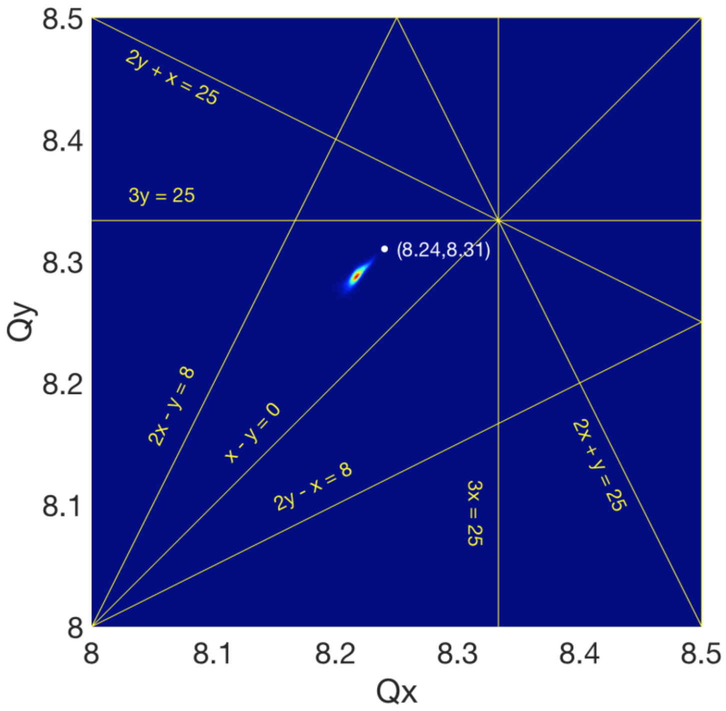
# Beam painting for the ESSnuSB AR (anti-correlated painting )

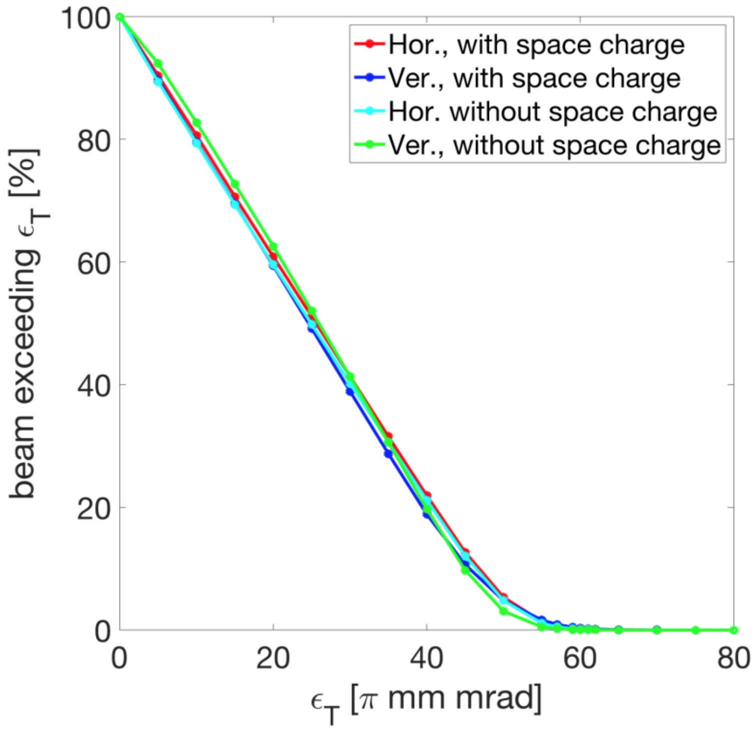
| Basic parameters for simulations | Value |
|---|---|
| Hor./Ver. Norm. rms emittance | 0.35 mm mrad |
| Extraction gap | 133 ns |
| Energy spread, 1 sigma | 0.02% |
| Foil thickness | 500 μg/cm$^2$ |
| Hor./Ver. beta function at injection point | 10 m/ 20 m |
| Hor./Ver. tune | 8.24/8.31 |
| Injection turns | 597 |
| Macro particles per turn | 500 |
| Pulse length per turn | 1.2 μs |
| Beam intensity per turn | $3.7\times10^{11}$ |
| Barrier RF voltage | 5 kV |
| Barrier RF phase | 162 deg |

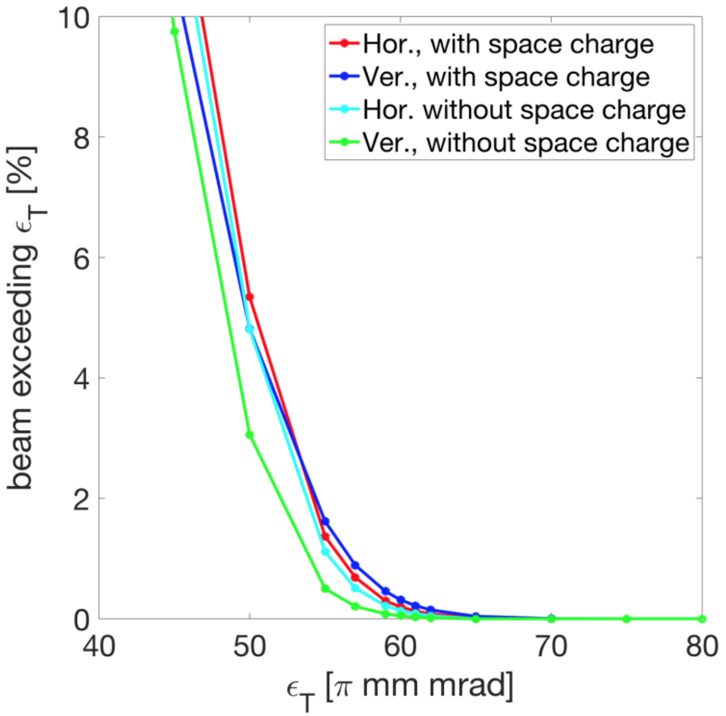
Simulation with PyORBIT



# Tune and Emittance (anti-correlated painting)



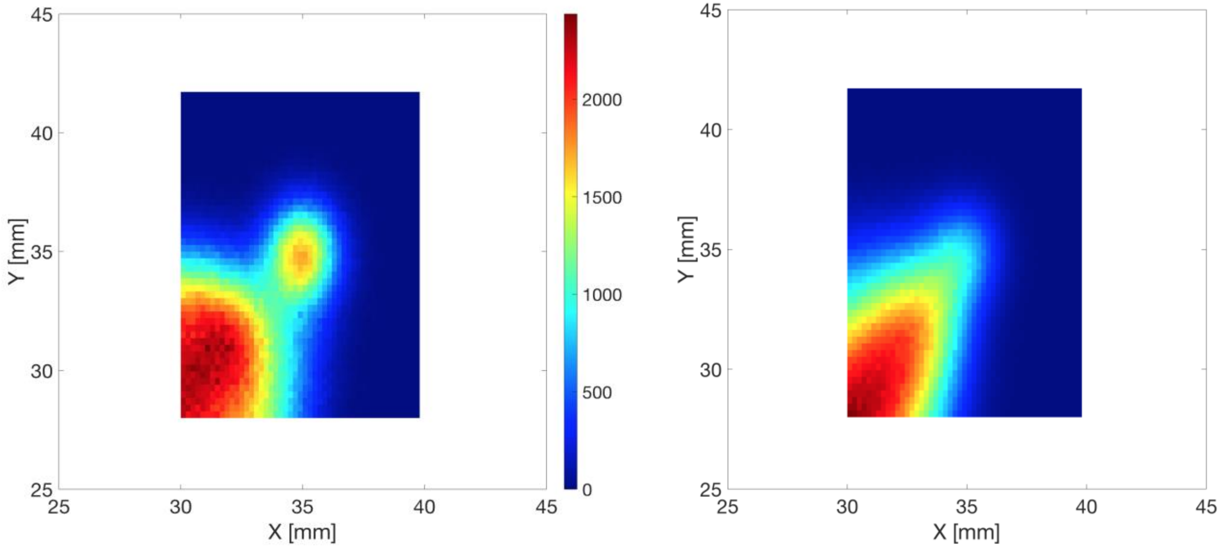




- Very small tune spread (~0.05), which fits the calculation results
- 100% beam emittance: 59 π mm mrad in horizontal and 60 π mm mrad in vertical plane
- RMS emittance: 12.9 π mm mrad in horizontal and 12.5 π mm mrad in vertical plane

# Foil temperature mitigation

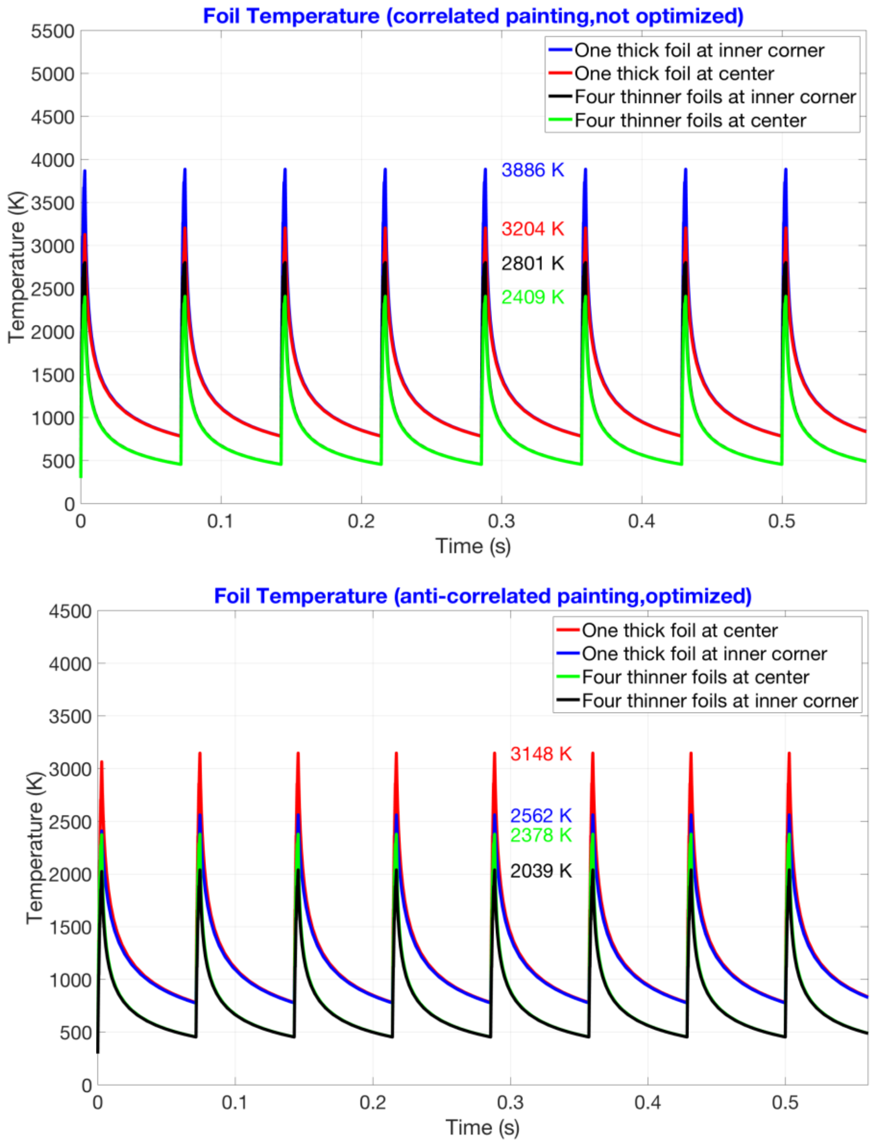
- Foil temperature issue is very serious which can decrease the foil lifetime sharply when temperature exceeds 2000 K
- Several methods are considered to mitigate the peak temperature on the foil:
  - A good painting can decrease the peak foil temperature at inner corner
  - Splitting-foil scheme: splitting the foil into several thinner ones with the same total thickness along the beam, which can lower the peak temperature at both center and corner
  - Mismatched injection to mitigate temperature rise
  - Moving injection point or adopting several foils along horizontal plane is also considered

# Foil-hits distribution and foil temperature




Good painting

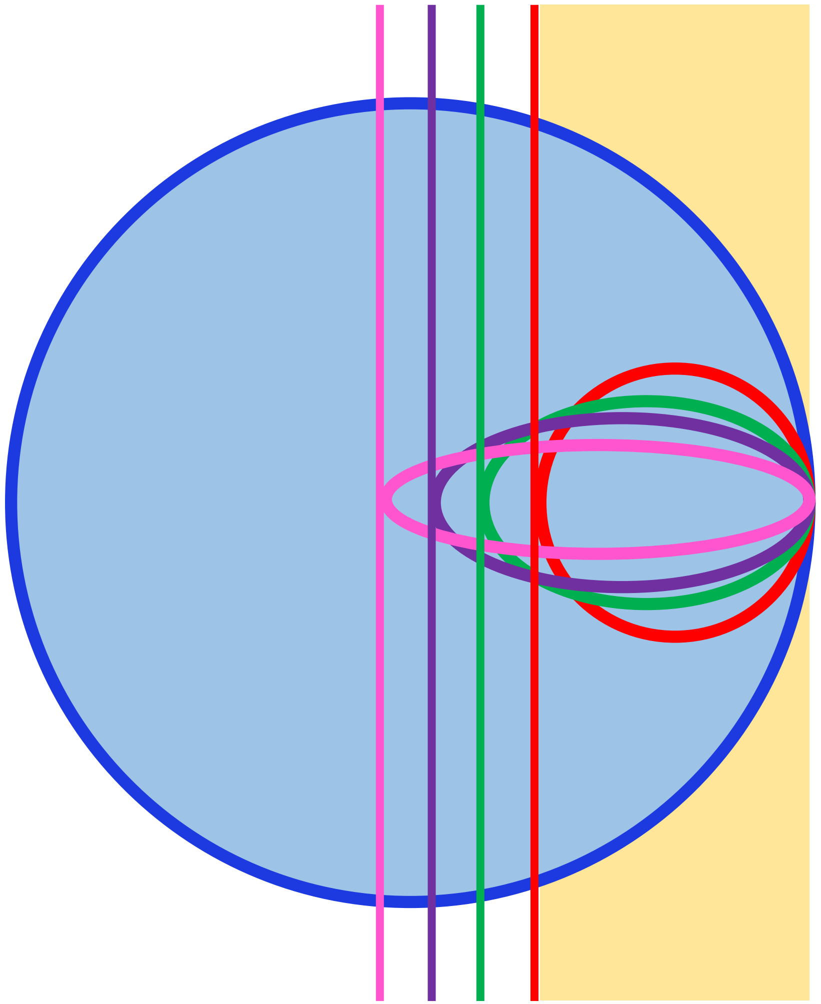
Not good painting




A good painting and splitting-foil scheme can dramatically reduce the peak temperature of the foil, however, peak temperature still exceeds 2000 K.

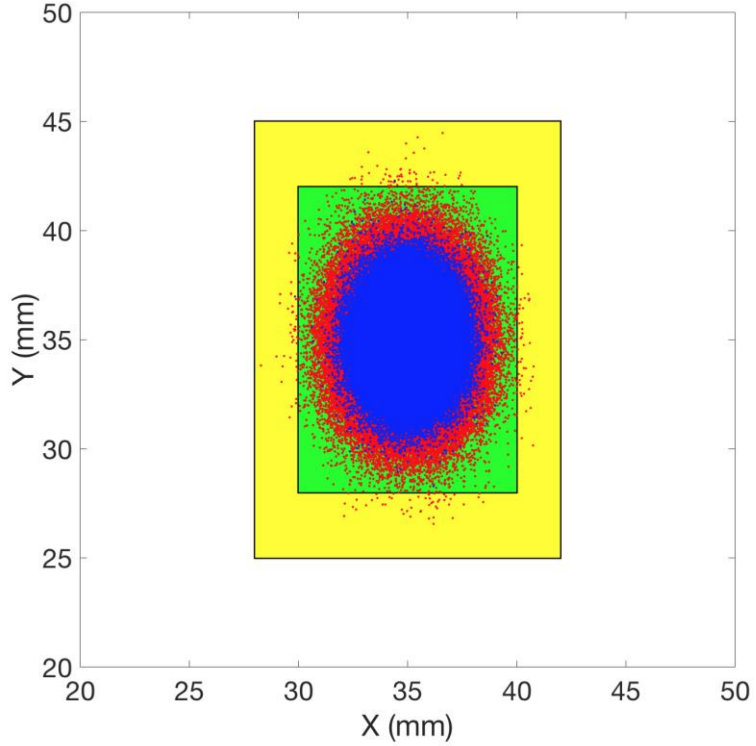
# Mismatched injection

- In general match all the physical parameters of the linac and ring at injection point is a primary concern
- 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)
- Mismatched injection need foil in larger size than matched injection and average foil hits will increase

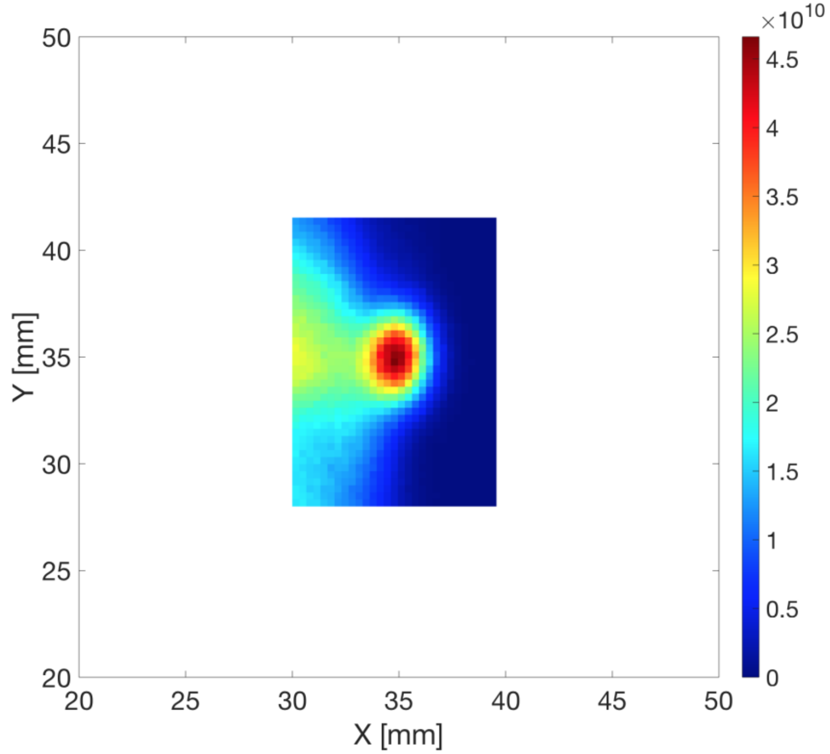


# Mismatched injection

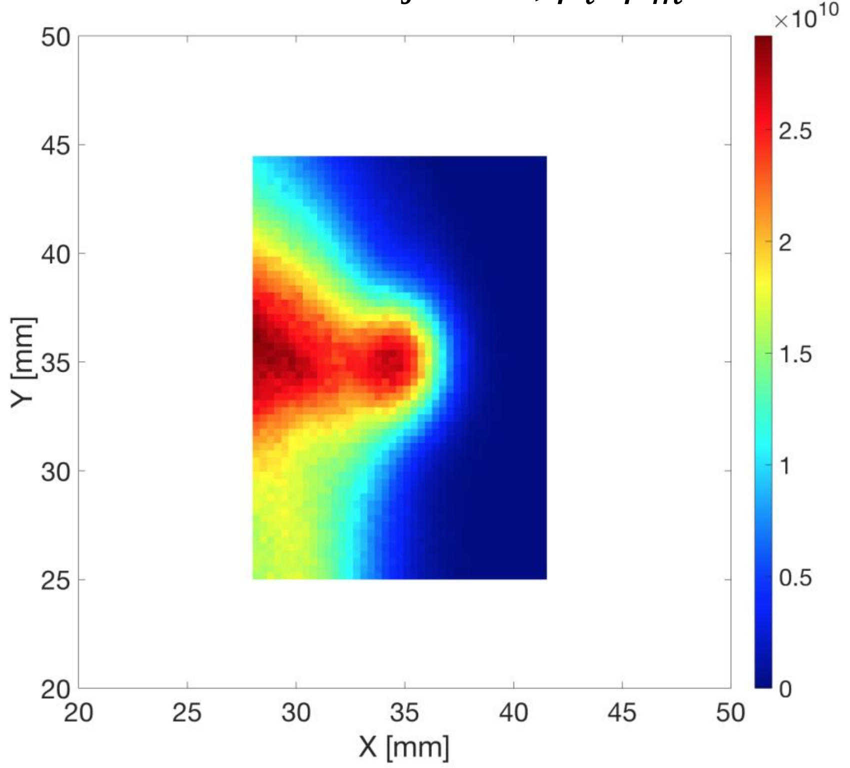
Injected beam distribution and foil




Energy deposition (4 batches) for matched injection, $\beta_i / \beta_m$=1

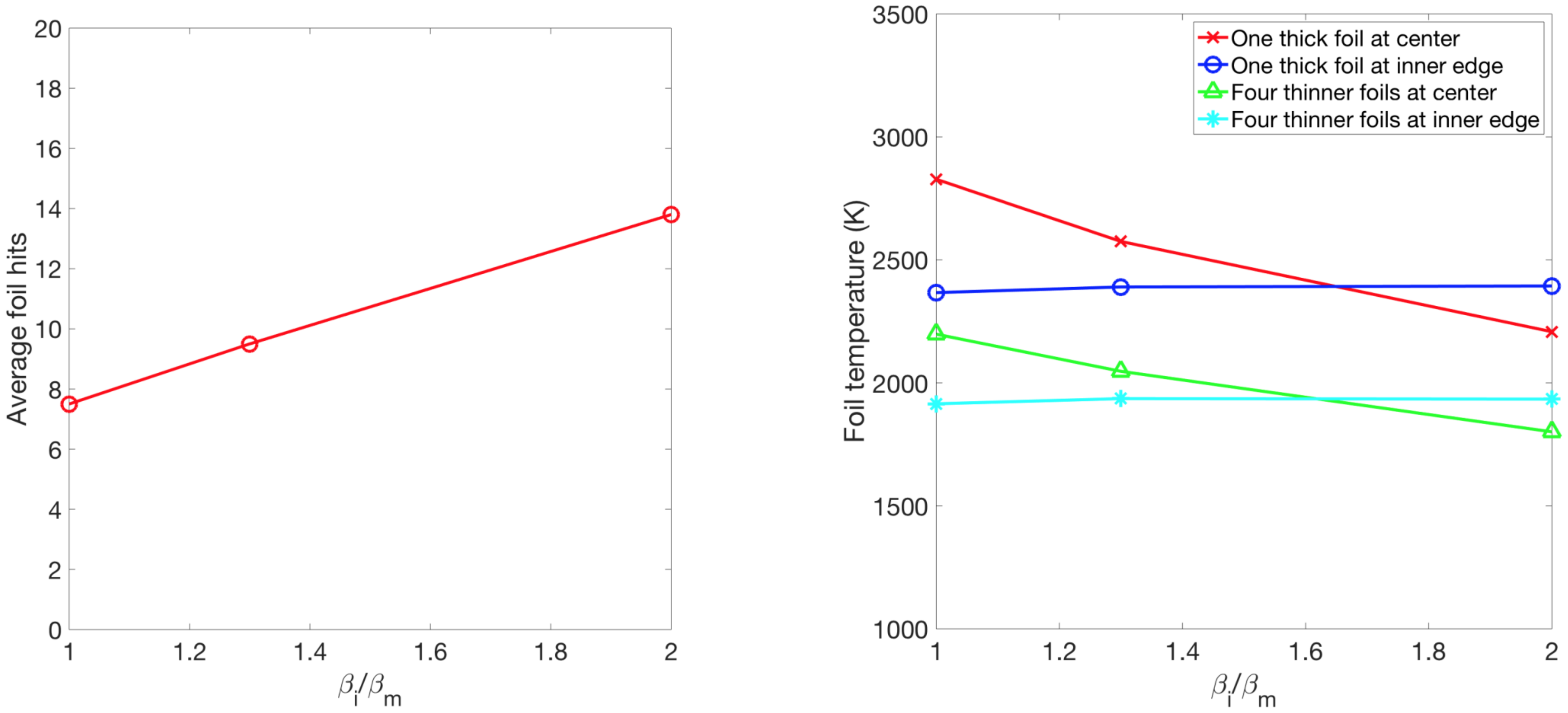



Energy deposition (4 batches) for Mismatched injection, $\beta_i / \beta_m$=2



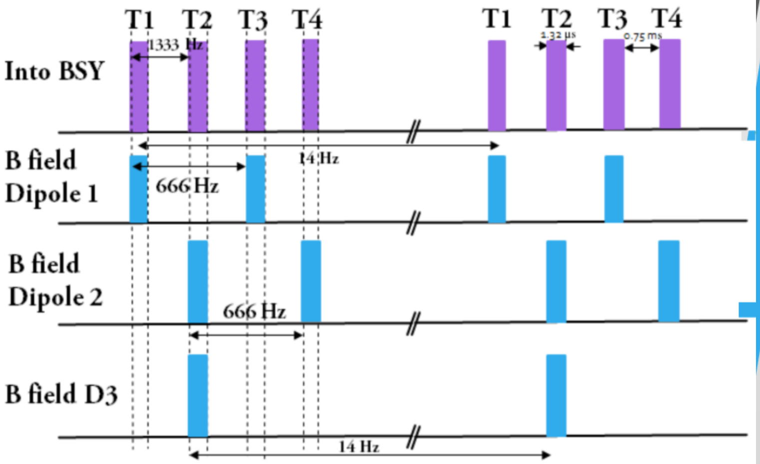

Peak energy deposition $4.0\times10^{10}$ J/m$^3$ for matched injection and $2.4\times10^{10}$ J/m$^3$ for mismatched injection

# Foil average hits and temperature

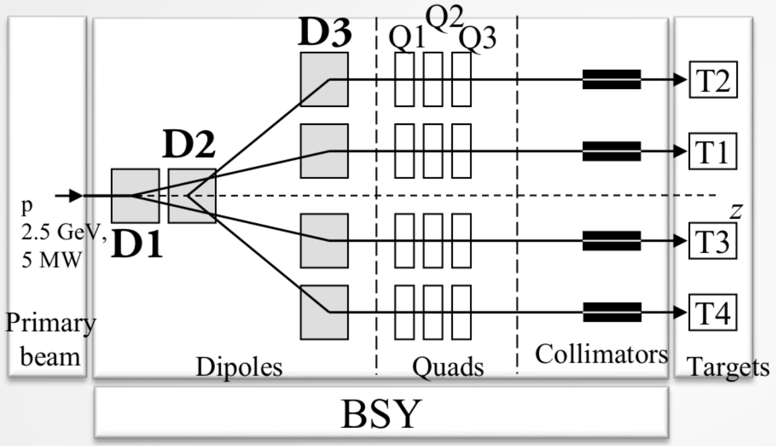



The maximum temperature can be lowered to 2000 K for a good anti-correlated painting, mismatched injection at $\beta_i/\ \beta_m$=2 and with splitting-foil scheme

# The Switchyard




## Updates of the principle 1



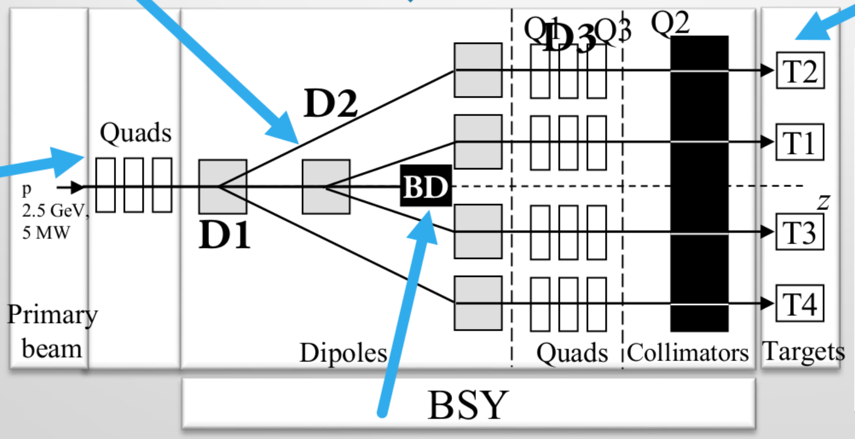

May 2019

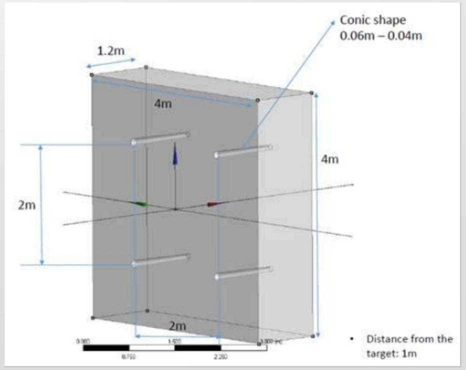
Sept. 2019

The beam deflected by D1 does not go through D2 but outside (to relax the constraints of D2 having consequent aperture)

Use of a single block of (carbon?) for collimation instead of 4 collimators

Addition of a triplet of quadrupoles at the entrance of the BSY

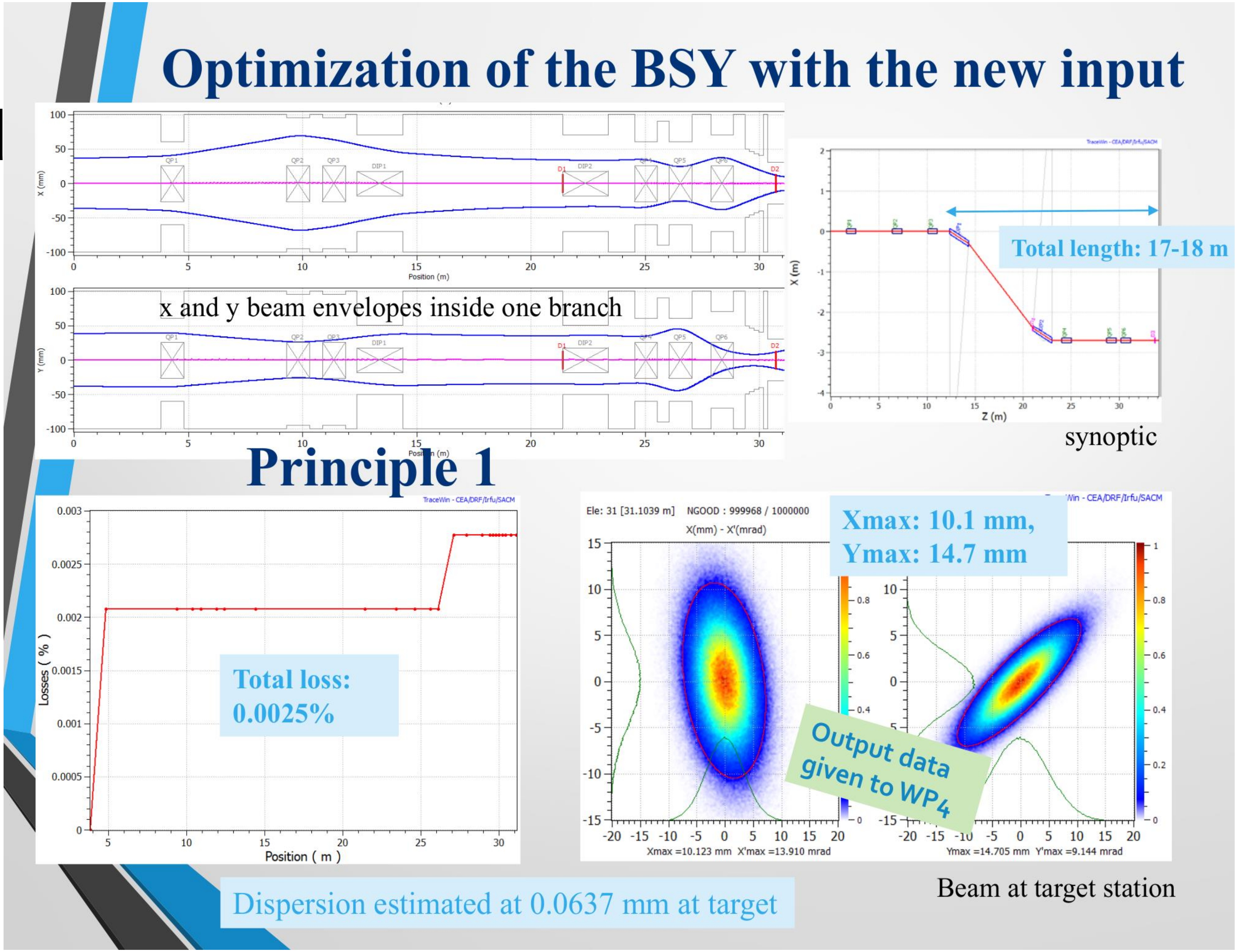



Addition of a beam dump after the 2 first dipoles

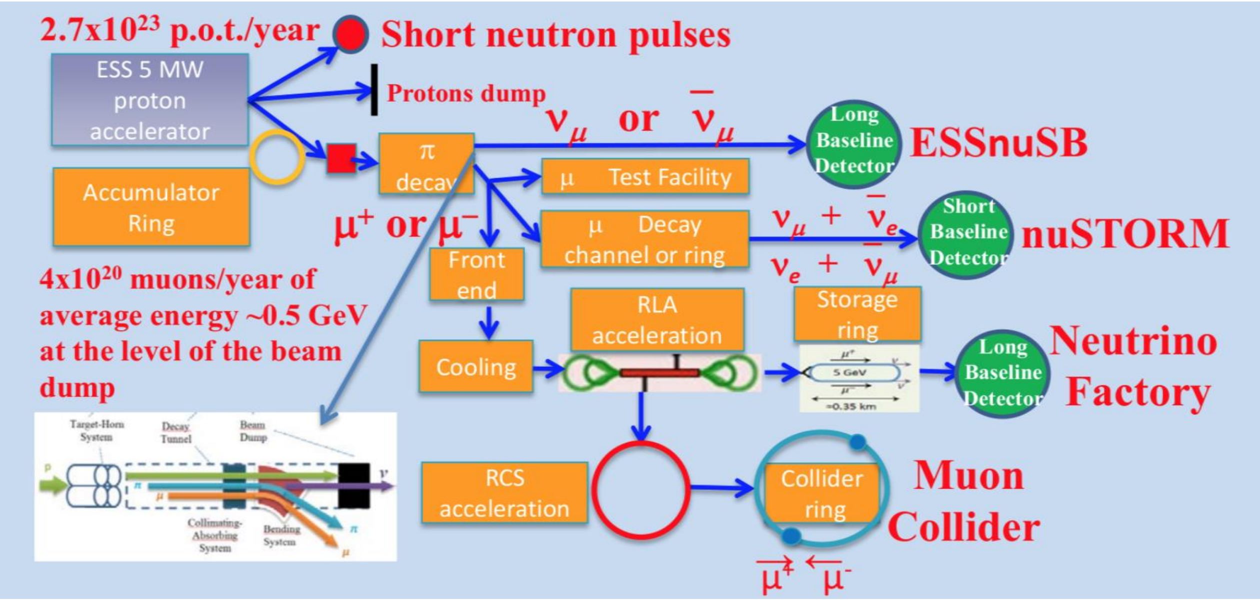
Elian Bouquerel

# The Switchyard




Elian Bouquerel

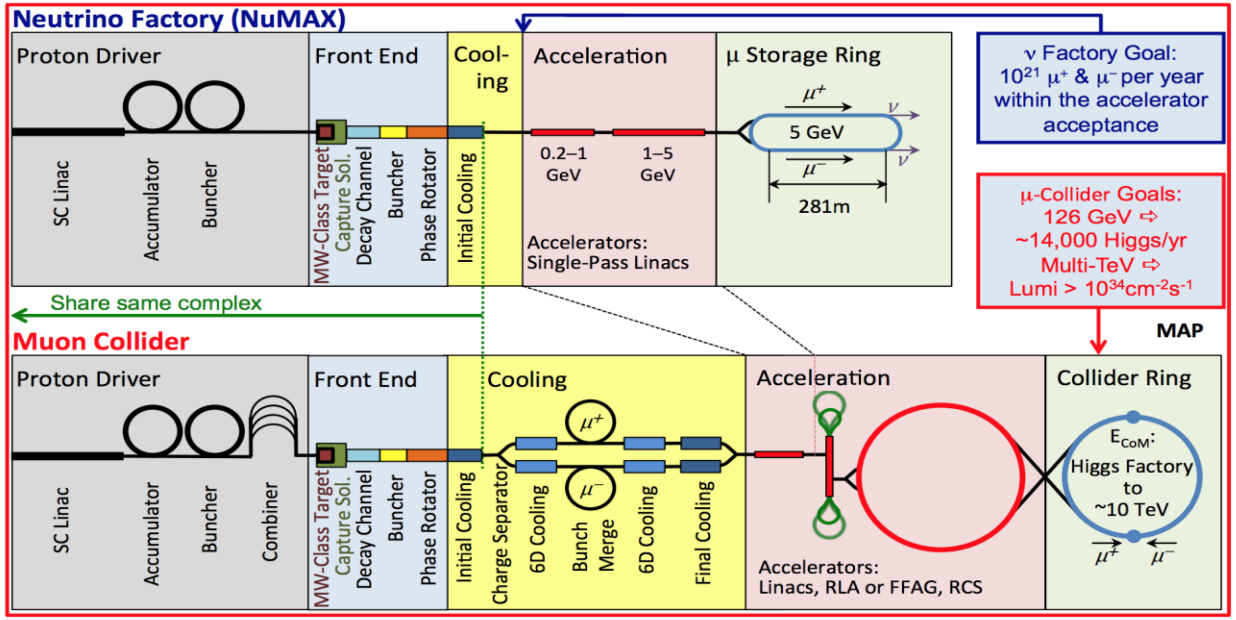
# Synergies with other proposals




- Similar design for different proposals
- Pulse structure in the linac and on the target
- Beam intensity for each filling, injection turns, circulating turns after injection, extraction

- $H^-$ injection, $H^-$ stripping and beam painting
- RF cavities adopted to keep gap clean for extraction
- A robust collimation system
- Transfer line and switchyard similar design
- Foil stripping most challenge

From Jaroslaw Pasternak's talk



# 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: ~0.03, very small
- Extraction gap can be kept clean
- Foil temperature issues can be mitigated in several ways and can be kept no exceed 2000 K
- A new designed switchyard which has very small beam losses

## Still in progress:

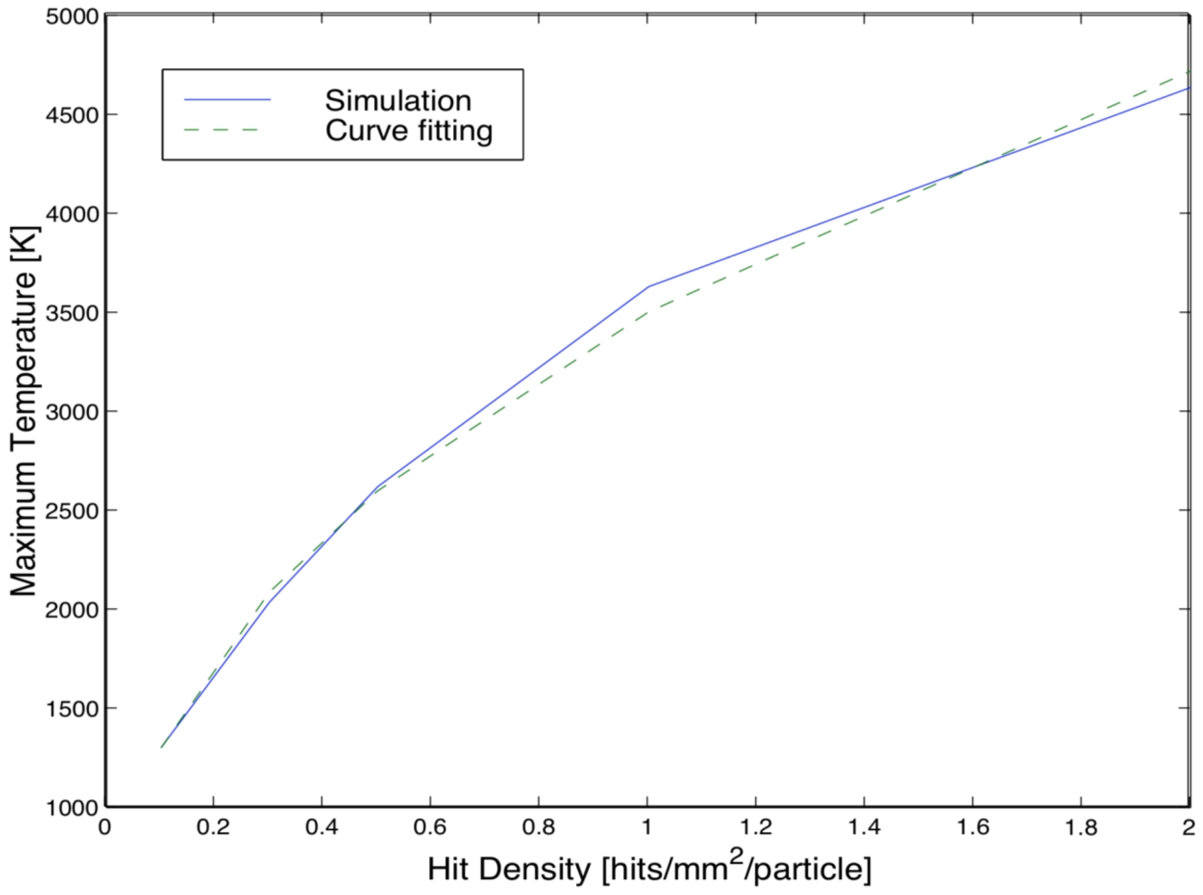
- Collimation system
- Chromaticity correction
- Beam extraction

# Back up slides

# Configurations for simulation

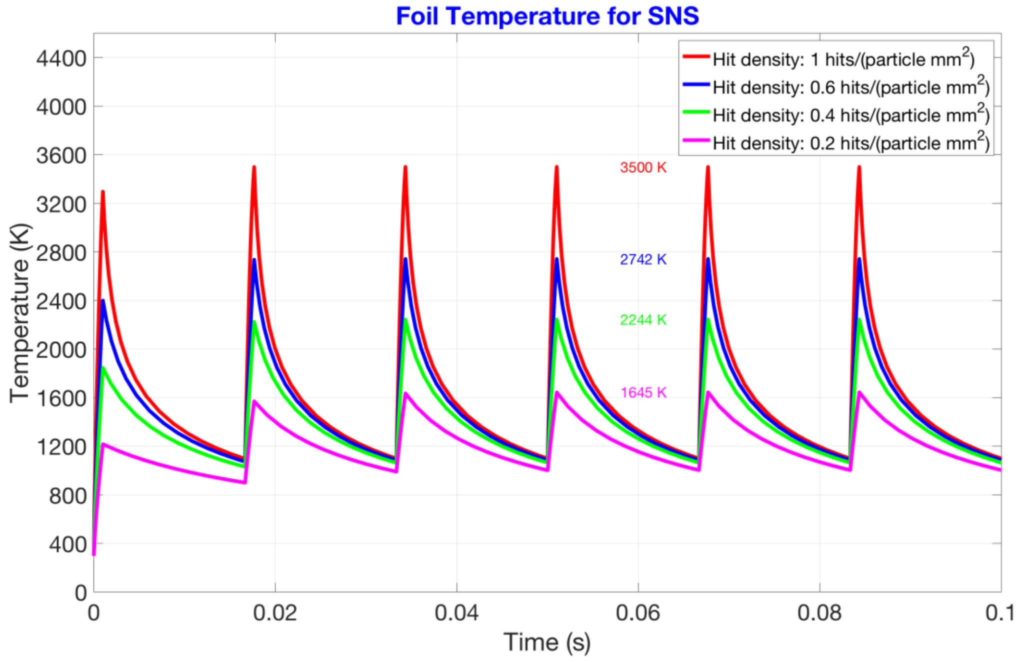
- Lattice developed by Horst Schonauer
- Simulation tools: PTC-PyORBIT
- Linac beam: Gaussian distribution in transverse plane and uniform in longitudinal
- Energy spread in Gaussian distribution
- On-momentum matched beam injection
- RF cavity: no RF cavity, dual harmonic RF cavity, barrier RF cavity
- Both direct and indirect space charge included
- Foil scattering included
- Chromaticity not corrected
- Correlated and anti-correlated painting

# 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 |



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- In general match all the physical parameters of the linac and ring at injection point is a primary concern.
- 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).
- Mismatched injection should satisfy two preferred conditions in order to efficiently stack injected turns in phase space:
  - $\frac{\alpha_i}{\beta_i} = \frac{\alpha_m}{\beta_m} = -\frac{X'_C}{X_C}$
  - $\frac{\beta_i}{\beta_m} \geq \left(\frac{\varepsilon_i}{\varepsilon_m}\right)^{1/3}$ Satisfied automatically if you want large spot size
  - $\alpha_i$, $\beta_i$, and $\varepsilon_i$ are Twiss parameters in the transfer line at the injection point and normalized RMS emittance of injected beam
  - $\alpha_m$, $\beta_m$, and $\varepsilon_m$ are Twiss parameters in the ring at the injection point and normalized total emittance after injection