UPPSALA UNIVERSITET

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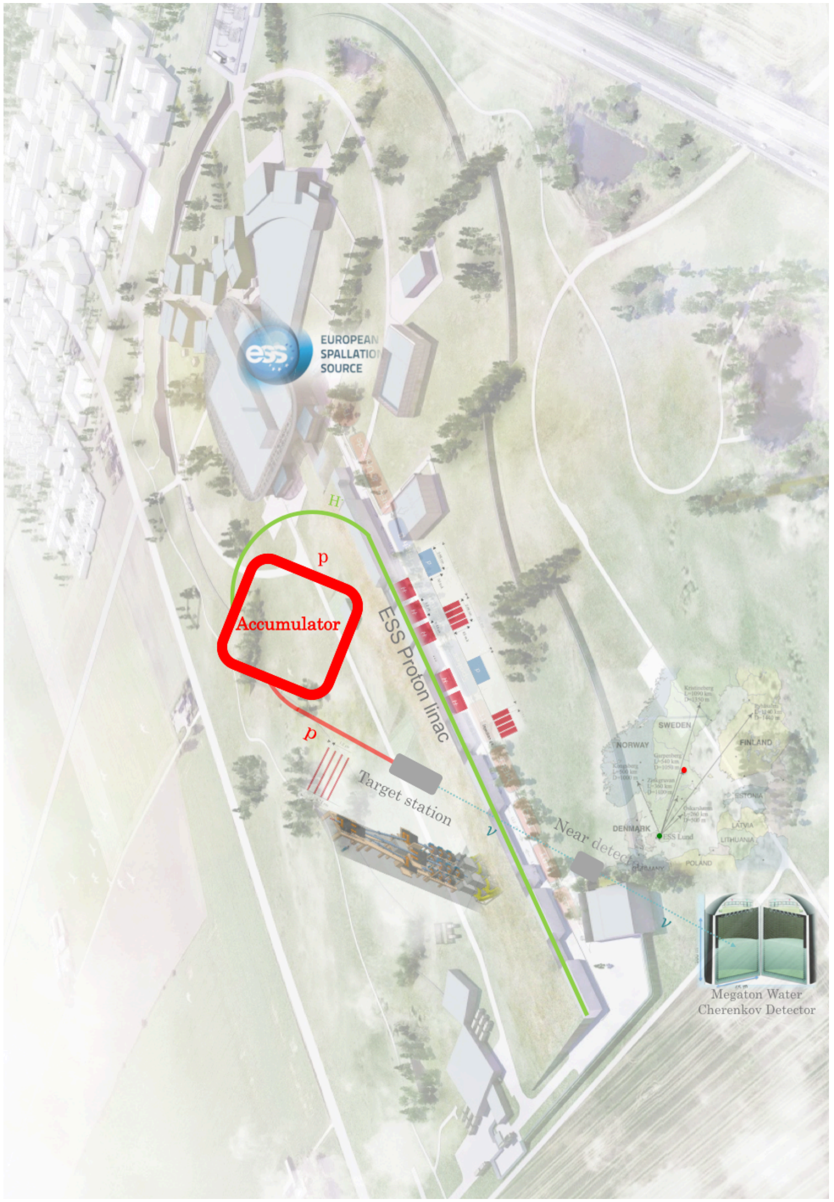
The accumulator ring for the ESSnuSB project

Ye Zou, Maja Olvegård, Uppsala University,
on behalf of the ESSnuSB WG3



EuroNuNet

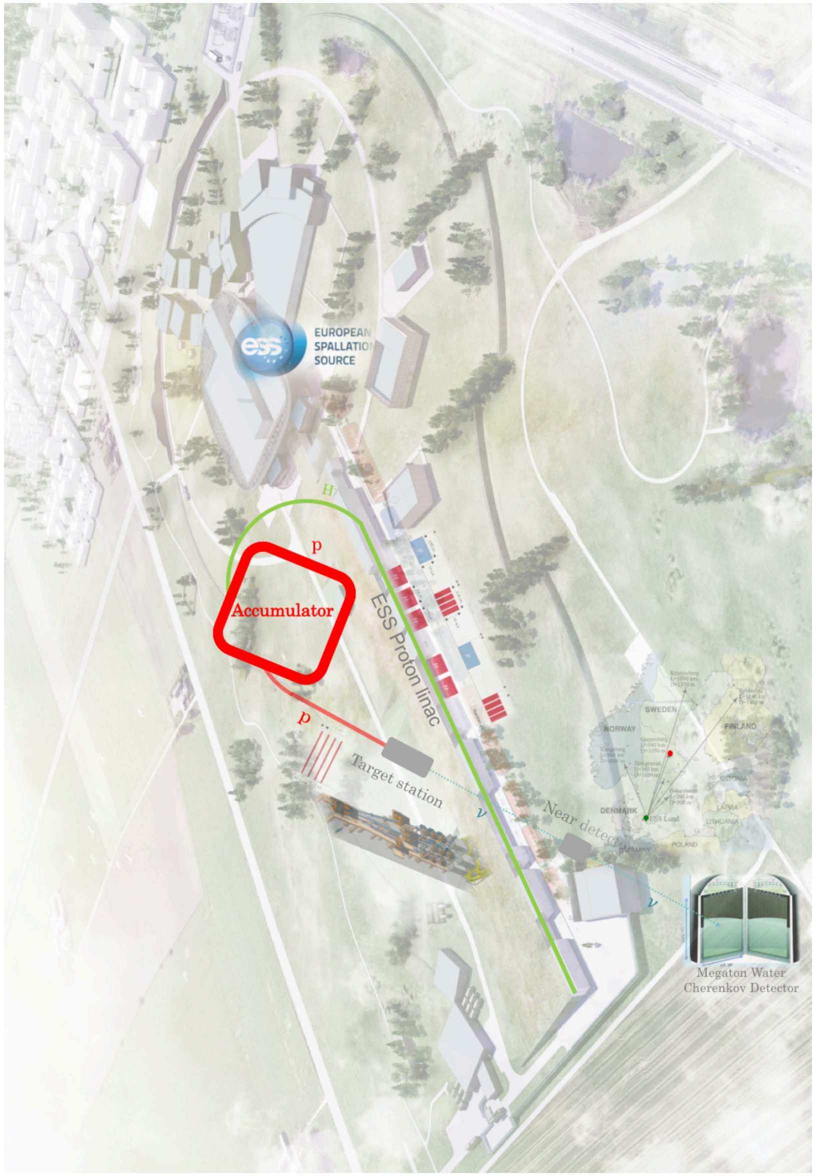
COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESS NEUTRINO SUPER BEAM

Outline

- ESS and its proton linac
- Accumulator ring design
- Multi-particle simulation
- Summary

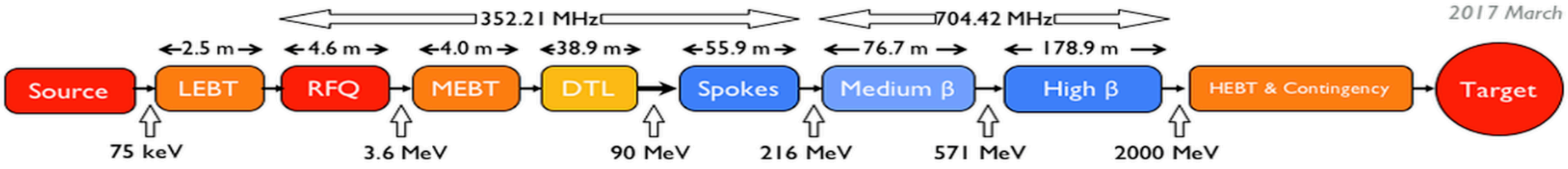
ESS and its proton linac



The European Spallation Source, ESS

Lund, Sweden

The ESS proton linac



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
Duty cycle	4%
Pulse repetition rate	14 Hz

> 2.7×10^{23} p.o.t/year by 2023

The ESS proton linac

Why to add the neutrino facility?

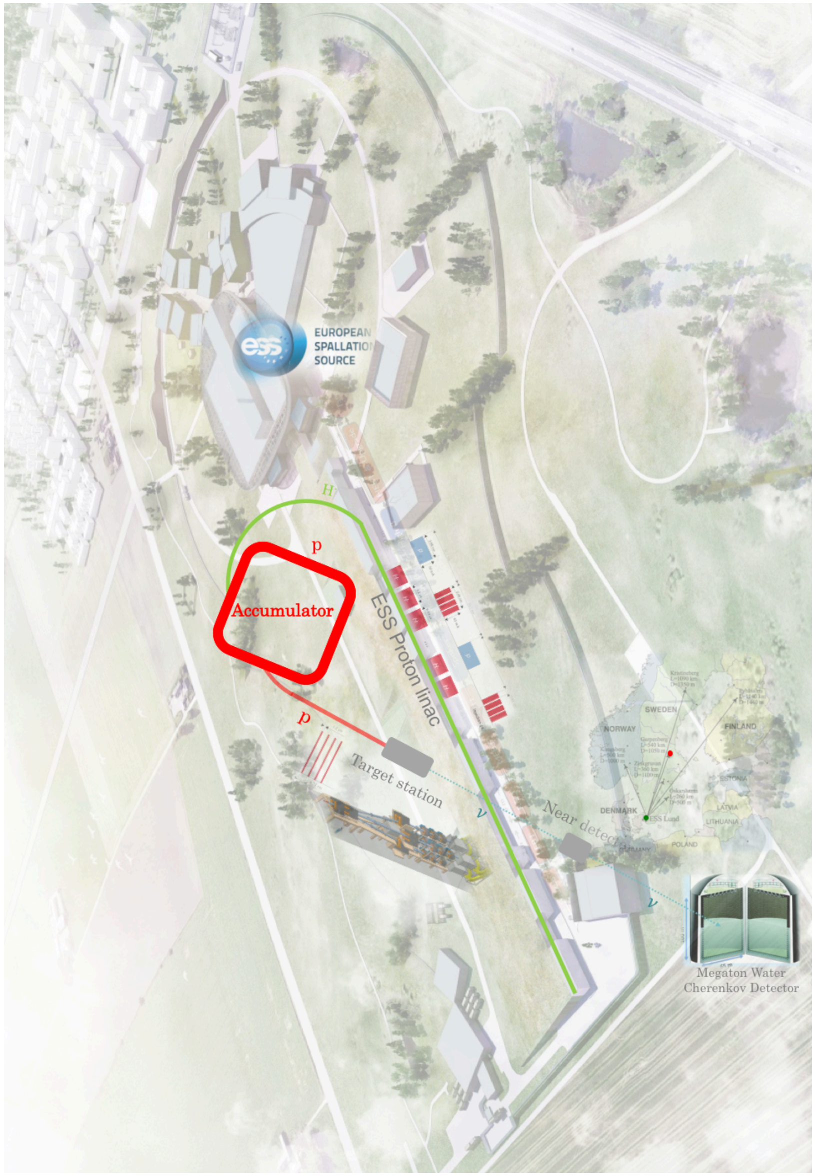
Because of the uniquely high power of the ESS linac we will have the opportunity to measure **with high precision** the neutrino CP-violating angle at the 2^{nd} oscillation maximum

How to add the neutrino facility?

Linac modifications (See Benjamin Folsom's talk)
Neutrino target station (See Loris D'Alessi's talk)
Underground detectors (See Jason Park's talk)

	What ESS Linac offers:		What neutrino target station requires (per target, 4 targets in total)
Accumulator ?	5 MW	Pulse divided into 4	< 1.6 MW
	2.86 ms	**Accumulator**	< 1.5 μs

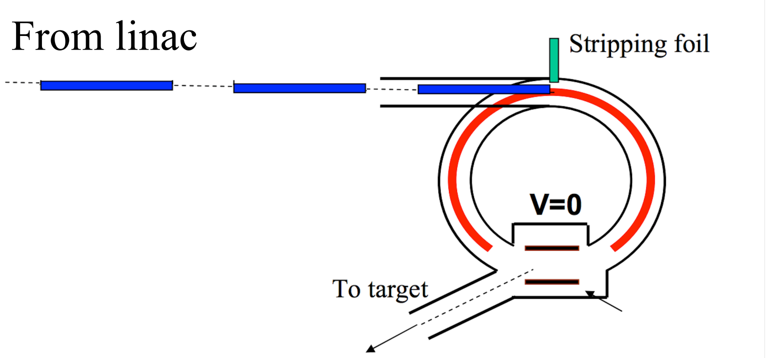
The accumulator design



Accumulator design

Compress the pulse from the ESS linac by 3 orders of magnitude before sending to the target

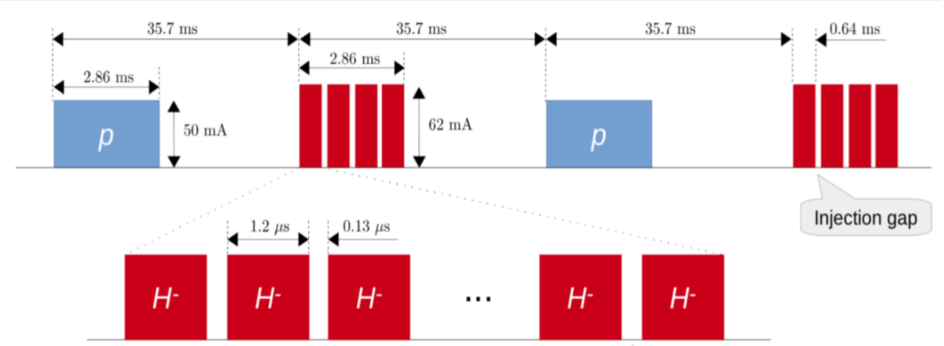
- Energy increases from 2 GeV to 2.5 GeV
- 5 MW pulse divided into 4 sub-pulses with 0.1 ms gaps in between
- Total pulse duration maintains 2.86 ms, each sub-pulse duration 0.64 ms
- Extraction pulse length < 1.5 µs, the circumference of the ring should be around 400 m, with a gap of ~10% for extraction
- Average beam current increase by ~20%
- Injection turns ~500
- Space-charge tune shift requirement: < 0.2



Beam loss control (1 W/m)

Total beam loss <10^{-4}

- A 99.7% geometric emittance of **100 π mm mrad**



Uncontrolled beam loss usually comes from high space charge induced tune shift, beam injection, limited transverse and momentum acceptance, instabilities and so on

Collimation efficiency ~ 90%

Beam halo power < 4 kW, beam halo < 0.3%

Accumulator design (ESSnuSB vs SNS)

Parameters	ESSnuSB AR	SNS (1.4 MW)
Beam power on target (MW)	1.25	1.4
Beam energy (GeV)	2.5	1.0
Beam intensity (ppp)	2.2×10^{14}	1.5×10^{14}
Average macro-pulse beam current (mA)	62	25
Pulse repetition rate (Hz)	14/1351	60
Macro-pulse length (ms)	0.64	1
Pulse length after accumulation (μs)	<1.5	0.7
Accumulation turns	~500	1070
Bunching factor	>0.9	0.25
Un-normalized painted beam emittance πmm-mr	100	300
Space charge tune shift	-0.03	-0.15

$$\Delta Q = -\frac{r_p n_t}{2\pi\beta^2\gamma^3\epsilon_{H,V}}\frac{F}{B_f}$$

Space charge tune shift

Challenge: Beam injection

Beam injection (H^- or p?)

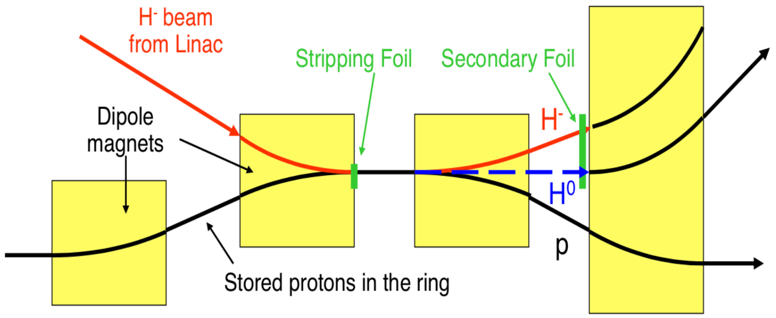
Proton: Liouvillean, Beam loss on septum unavoidable if many injection turns

H^-: Non-Liouvillean, proton can be overlaid on H^- in phase space
Circulating beam can also pass through the foil

H^- injection (foil stripping; following laser stripping development)

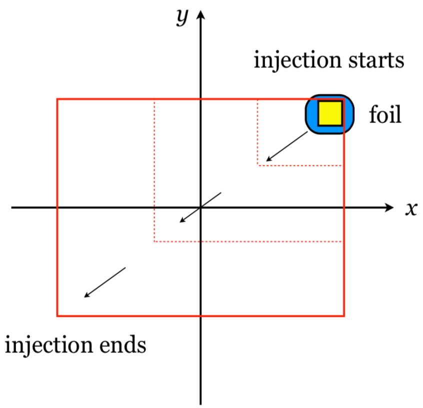
H^- beam passes through a thin foil, 2 electrons stripped by the foil to make H^- become proton

- Stripping efficiency
- Foil temperature
- Foil scattering (~10^{-5})
- H^{0*} (n=4, 5)
- Radiation
- Stripped electrons (~10^{-2})

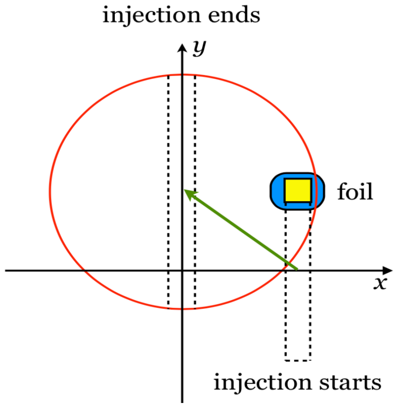


Transverse injection painting

- Painting beam can reduce space charge effect, and mitigate peak foil temperature
- Vary position of circulation beam at the foil by programming orbit bumps (H and V) in a dispersion-free region

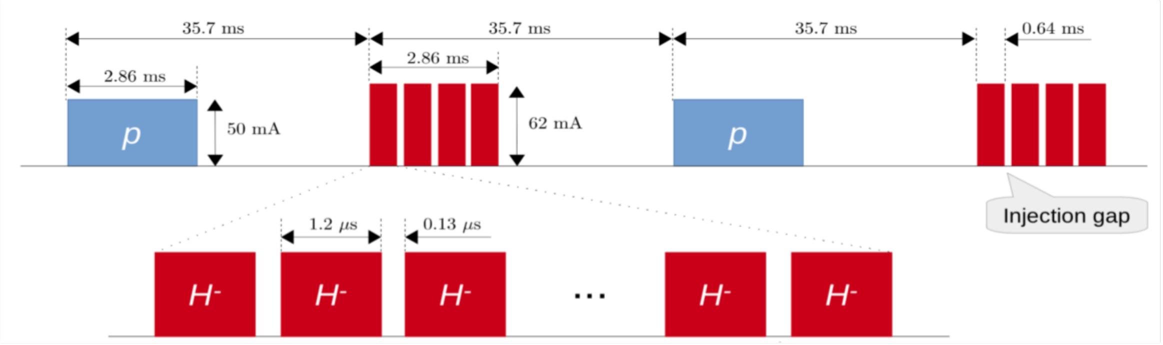


Correlated painting



Anti-correlated painting

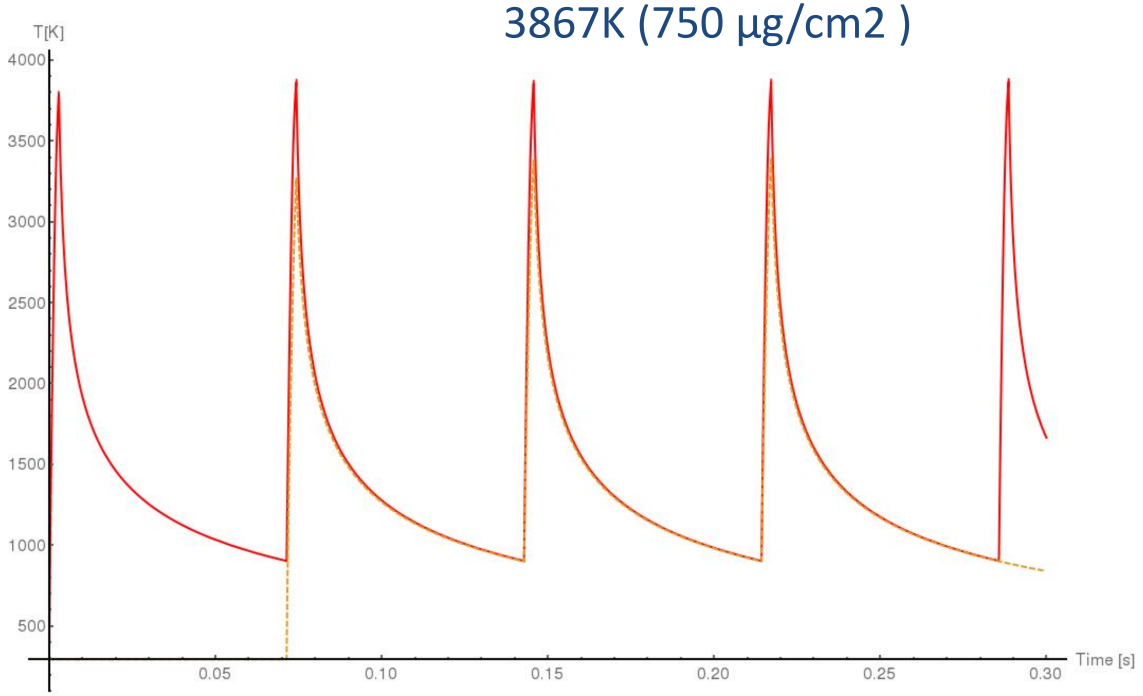
Challenge: Foil temperature



- Stripping foil does not have enough time to be cooling down between each sub-pulse, which makes the foil peak temperature too high

- Possible ways to mitigate the temperature rise
  - Putting several foils along the horizontal plane
  - Varying injection point on the foil

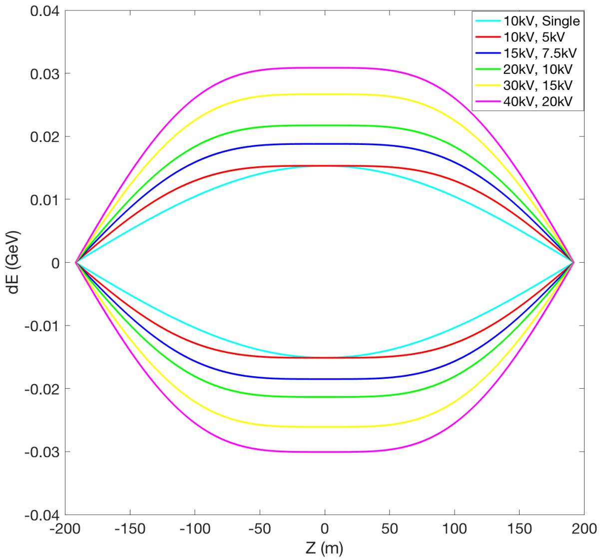
3867K (750 μg/cm2)



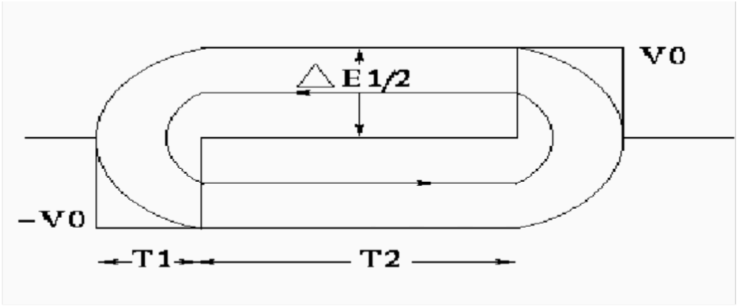
First calculation results from Horst Schonauer

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
- Energy spread increased due to very small longitudinal synchrotron oscillation frequency if single harmonic or dual-harmonic rf cavities implemented
- Barrier rf cavity only affect head and tail particles to keep the extraction gap clean



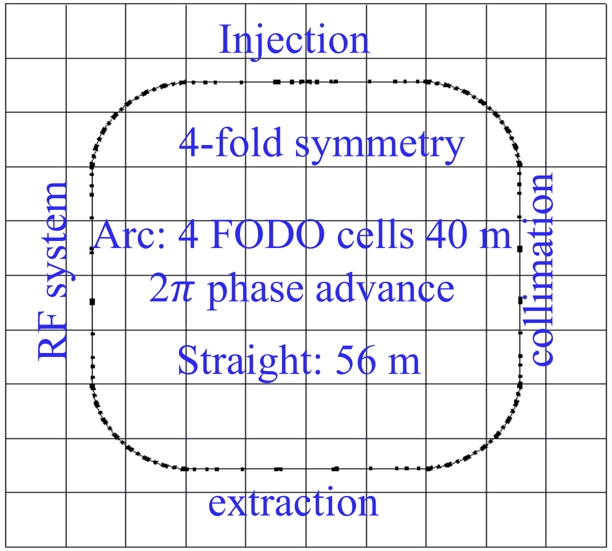
Single and dual harmonic rf bucket



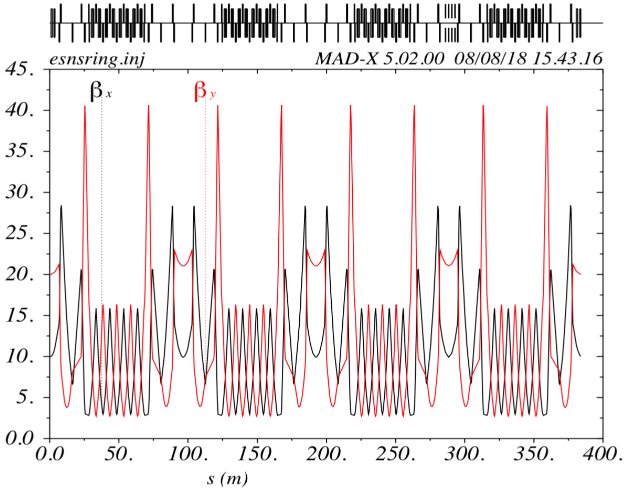
Barrier rf bucket

Lattice development

Developed by Horst Schonauer



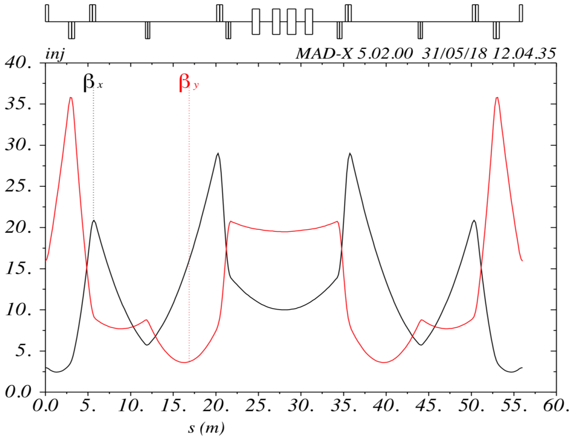
Layout of the lattice



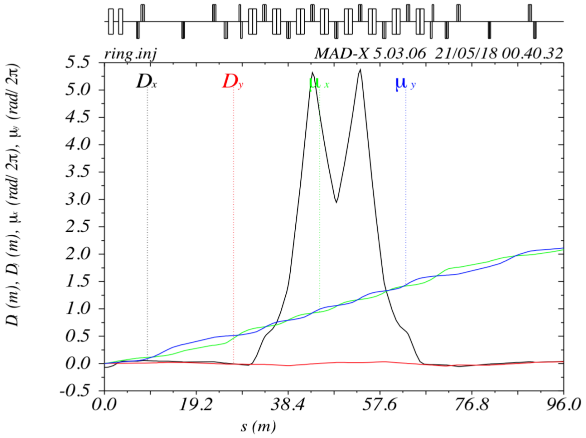
The whole ring

- Long straight section and enough phase advance for beam injection and collimation
- Fixed injection chicane (9 cm) and fast programmable bump for injection painting
- The β-function perturbation caused by the injection chicane and the orbit bumps is less than 2%

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	8.2-8.3/8.3-8.4	6.3/5.8
Transition energy, γ_T (GeV)	5.8	4.95
Hor./Ver. natural chromaticity	-11.2/-12.4	-7.5/-6.3
Number of superperiods	4	4

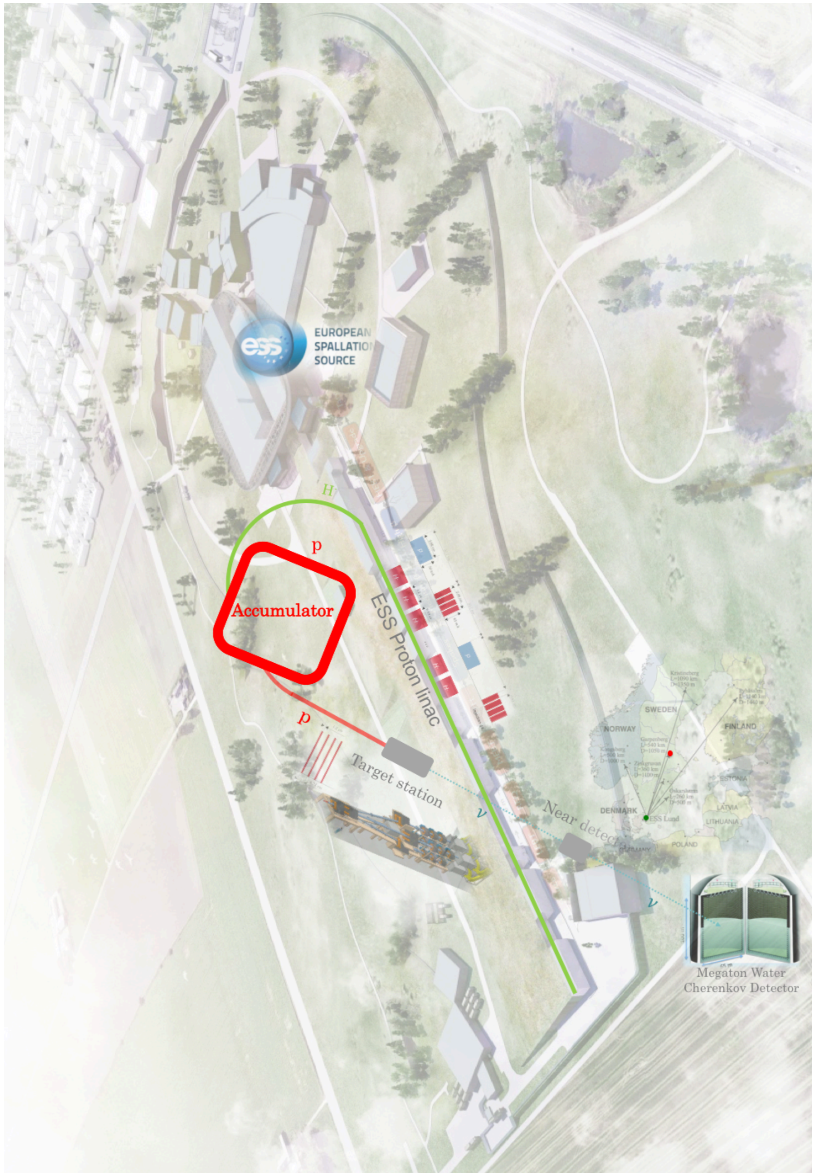


Injection section



Dispersion and phase advance

Multi-particle simulation



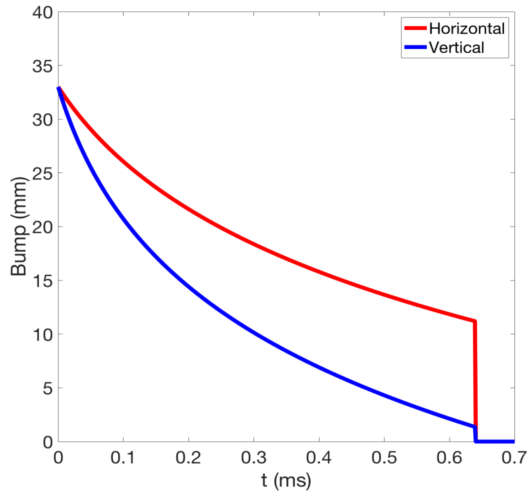
Configurations for simulation

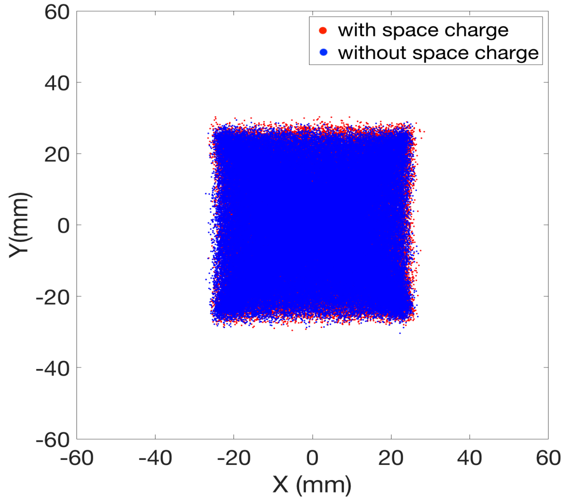
- Lattice developed by Horst Schonauer
- Simulation tools: PTC-PyORBIT
- Linac beam: Gaussian distribution in transverse plane and uniform in longitudinal
- Energy spread in Gaussian distribution
- On-momentum matched beam injection
- RF cavity: no RF cavity, dual harmonic RF cavity, barrier RF cavity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

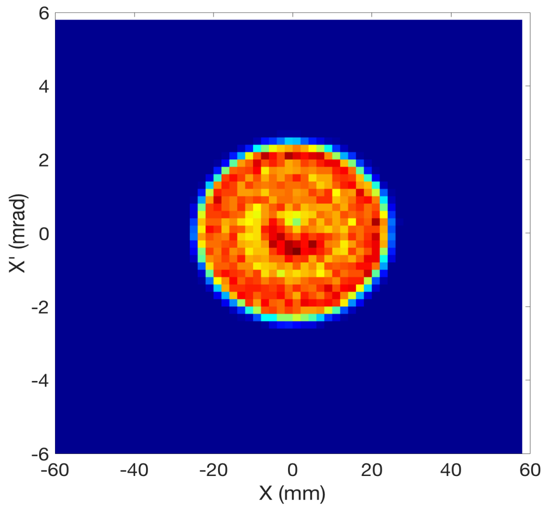
Basic parameters for simulations	**Value**
Hor./Ver. normalized rms emittance	0.35 mm mrad
Extraction gap	133 ns
Energy spread, 1 sigma	0.02%
Foil thickness	600 $\mu g/cm^2$
Hor./Ver. beta function at injection point	10 m/ 20 m
Hor./Ver. tune	8.24/8.38
Injection turns	481
Macro particles per turn	300
Pulse length per turn	1.2 μs
Beam intensity per turn	4.7×10^{11}
Barrier RF voltage	10 kV
Barrier RF phase	160 deg

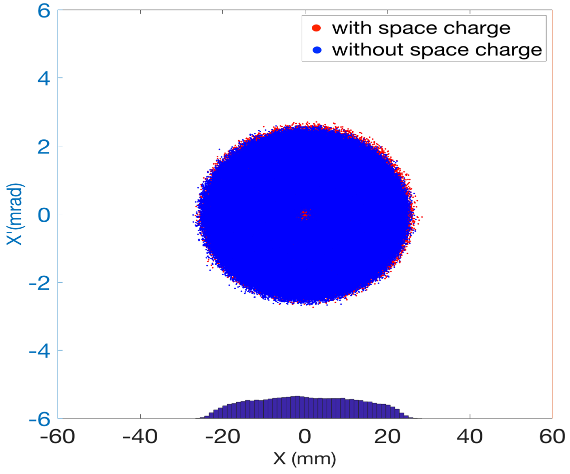
Transverse beam distribution (correlated painting)

- Bump varying in exponential-like function
- Painting from inner to outer both in horizontal and vertical planes
- Space charge has little effect on particle distribution for correlated painting
- The painting scheme can paint quite uniform beam distribution in both transverse planes



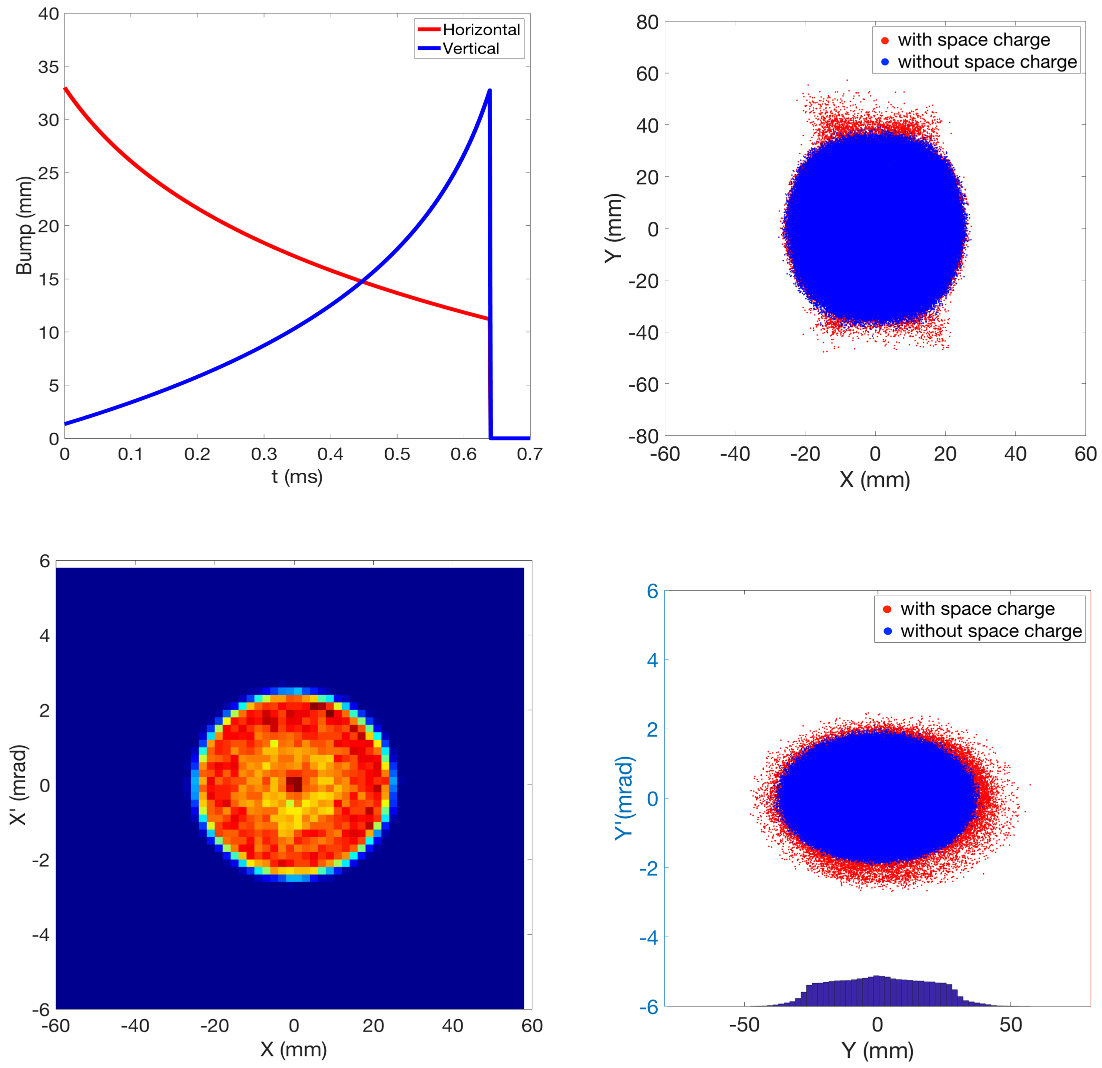




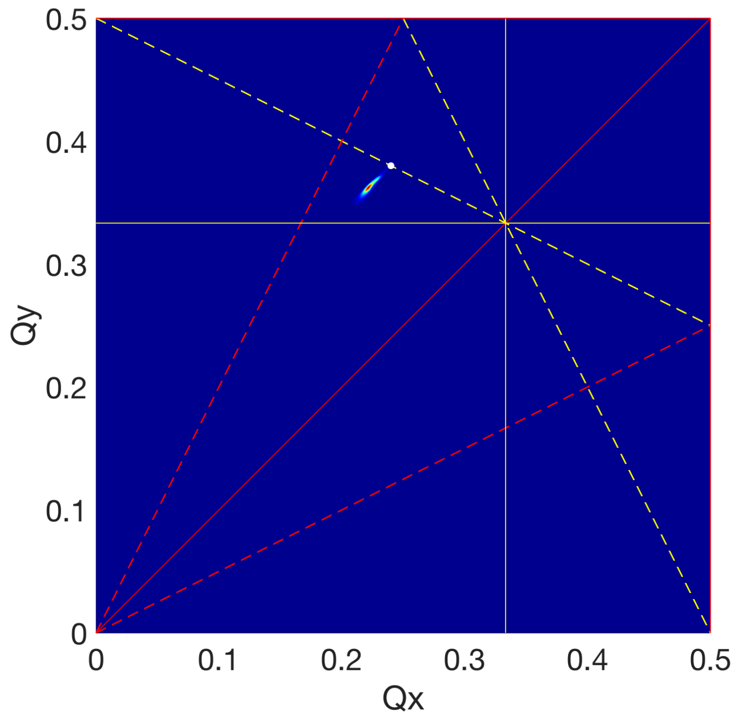


Transverse beam distribution (anti-correlated painting)

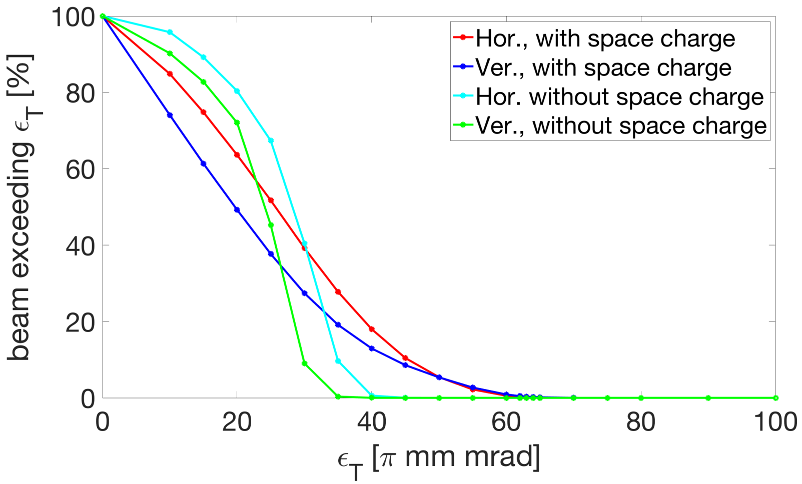
- Bump varying in exponential-like function
- Painting in horizontal plane from inner to outer, in vertical plane from outer to inner
- Some beam halo exists in vertical plane due to anti-correlated painting scheme
- The painting scheme can paint quite uniform beam distribution as well



Tune and Emittance (correlated painting)



The fractional number of particles falling outside a particular normalized emittance



- Very small tune spread (~0.05), which fits the calculation results

- 99.7% beam emittance: about 62 π mm mrad in horizontal and 63 π mm mrad in vertical plane
- Average foil hits:
  - Correlated 4.5 (SNS 2.7)
  - Anti-correlated 5.8 (SNS 5.0)
- RMS emittance: about 13 π mm mrad in horizontal and 11 π mm mrad in vertical plane
- Optimization ongoing.

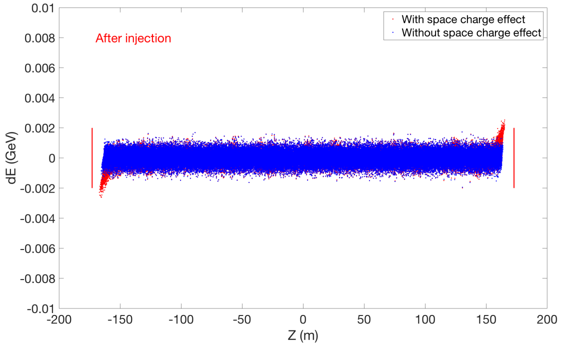
- If superperiods =1, red and yellow lines
- if superperiods =4, only red lines
- A higher superperiodicity is better

Longitudinal beam distribution

Two main points

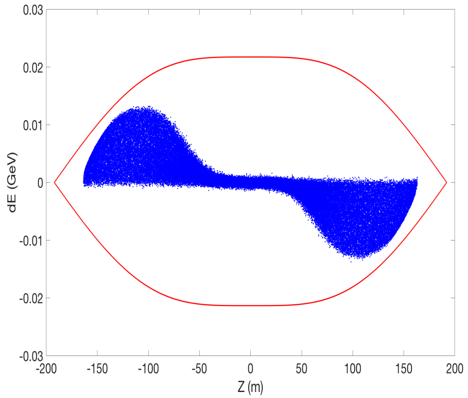
Point 1: Keep extraction gap clean during the whole accumulation process
Point 2: Minimize the energy spread

No RF cavity



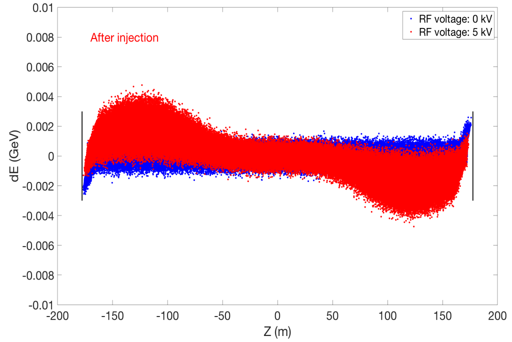
Point 1: large risk to leak
Point 2: excellent (~ ±0.1%)

Dual Harmonic RF cavity (High voltage, >10kV)



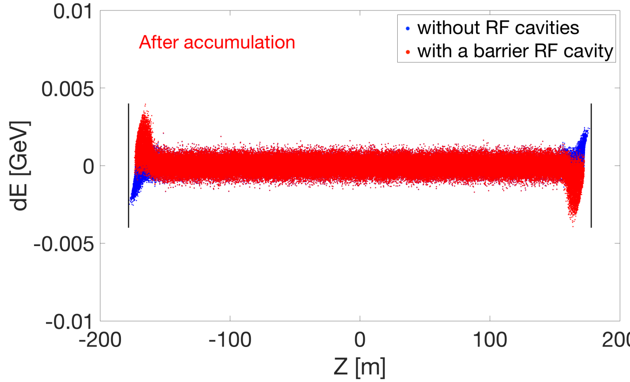
Point 1: excellent
Point 2: large energy spread (~ ±0.6%)

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 (~ ±0.2%)

- Beam is quite stiff
- Particles leakage to the gap would be possible without RF cavity
- Quite large energy spread if dual harmonic rf cavity with high voltage (>10 kV)
- 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

Summary and outlook

Where we are now:

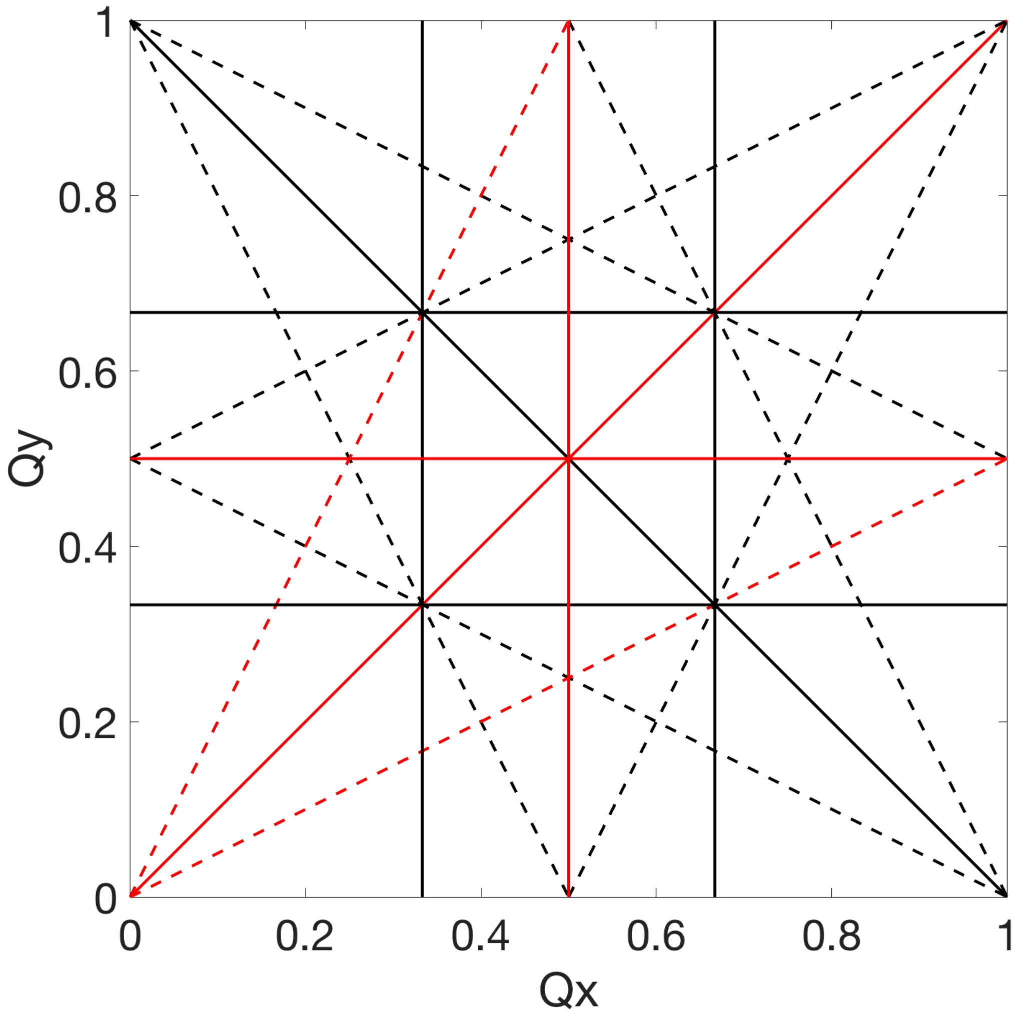
- Good lattice
- Quite uniform painting results
- 99.7% geometric emittance ~62 π mm mrad
- Tune spread: ~0.05
- Extraction gap kept clean well

What we plan to do

- Foil temperature mitigation
- Dynamic aperture studies
- Chromaticity correction
- Collimation system
- …

Back-up slides

Resonance and superperiods



- Tune spread induced by space charge effect, natural chromaticity, and magnet imperfection is unavoidable.
- Tune spread should be far from each order of resonance, in particular, low order resonance (<=3) due to possible beam loss
- Space-charge tune shift requirement: < 0.2
- Transverse resonance condition:

$$m\nu_x + n\nu_y = \mathrm{i}N$$

m,n,i,N integers, $l = |m| + |n|$ is the order of resonance, N is superperiodicity number.

- If N=1, black and red lines;
- if N=4, only red lines
- A higher superperiodicity is better

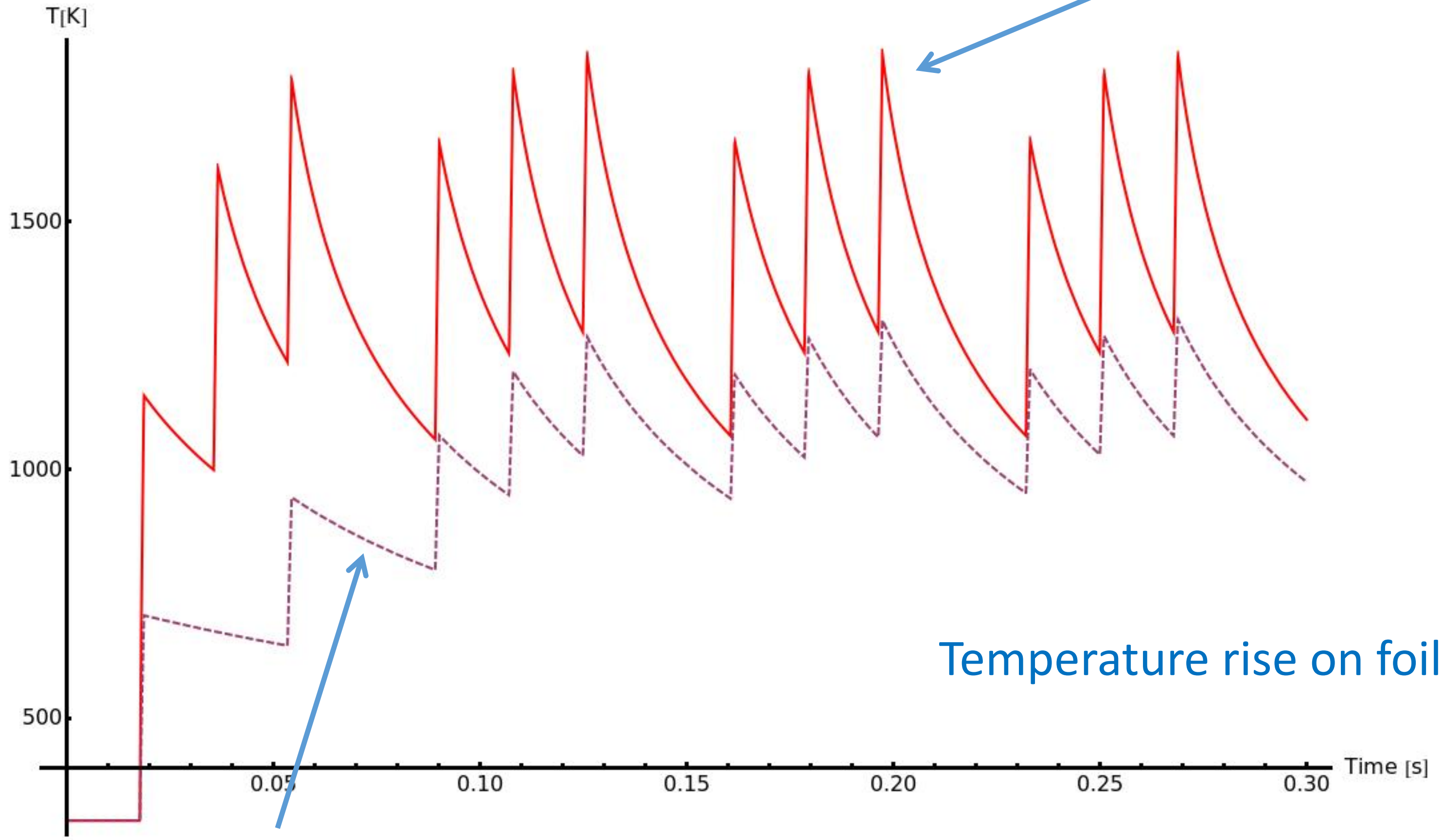
Temperature on foil for 56 Hz case

Horst Schönauer

Combined linac spot and circulating beam

3 batches from Linac

Not yet optimized

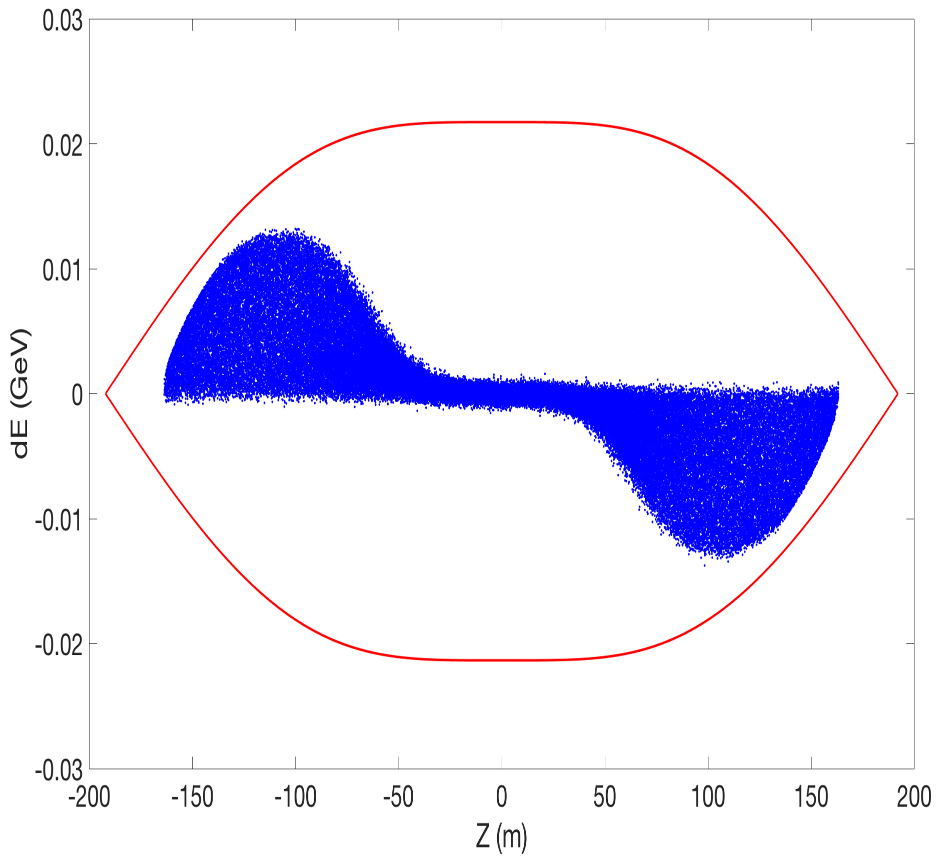


Linac spot

Temperature rise on foil seems acceptable

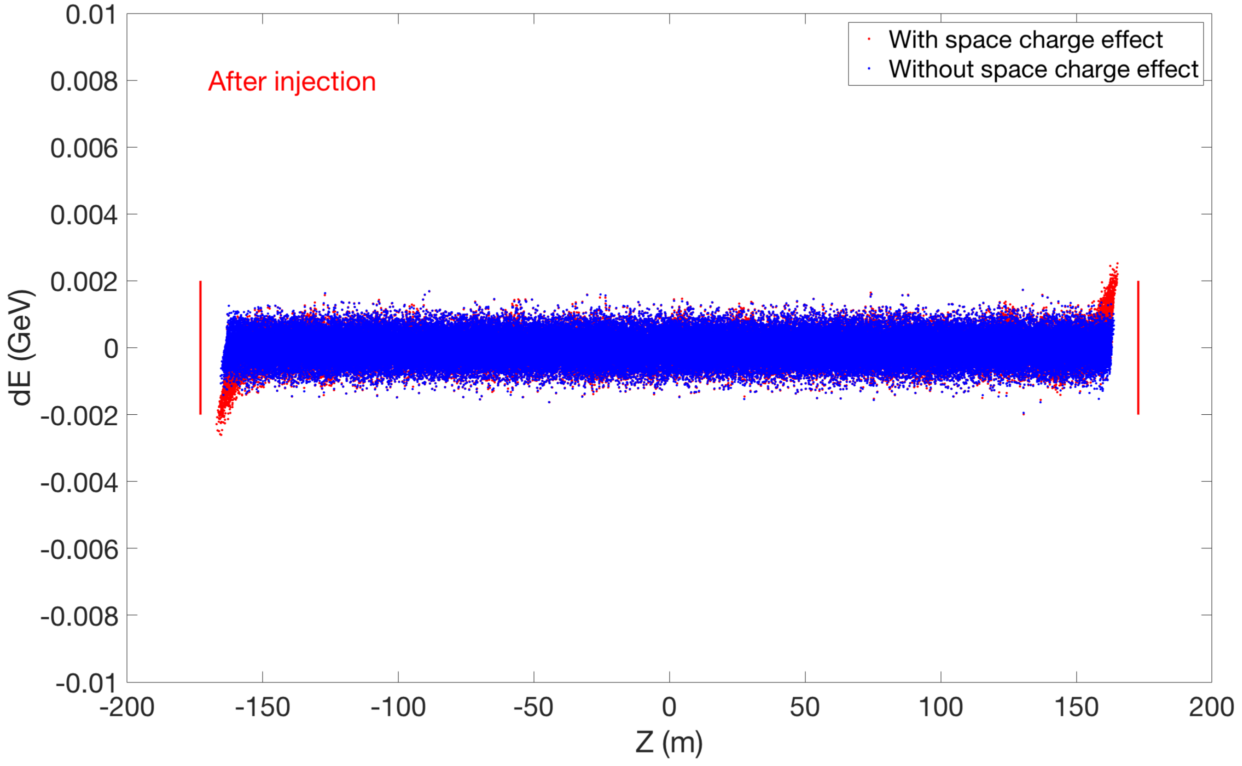
Longitudinal motion with dual-harmonic RF system

Beam distribution after injection



- Large energy spread (0.6%) caused by dual-harmonic RF cavity during longitudinal motion
- This energy spread could cause quite large tune spread (~0.14) due to nature chromaticity (-11.19, -12.41)
- The tune shift can be controlled by correcting the natural chromaticity with sextupoles, while this may introduce undesired nonlinear effects.

No RF cavities



- The beam is stiff enough
- Seems possible to maintain 100 ns gap for extraction without RF cavities at 2.5 GeV if only direct space charge considered
- Barrier RF cavities probably needed if indirect space charge considered

First consideration of collimation system

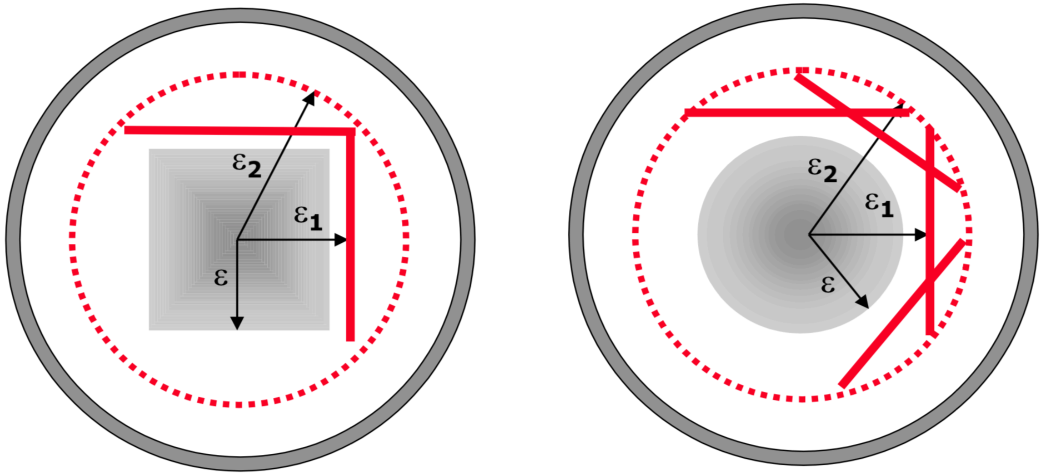
	SNS		ESSnuSB75		ESSnuSB100	
	Correlated	Anti-correlated	Correlated	Anti-correlated	Correlated	Anti-correlated
ε	120	160	75	75	100	100
ε_1	140	180	95	95	120	120
ε_2	280	200	190	115	240	140
Coll. Accept.	**300**		**200**		**260**	
Ring Accept.	**480**		**380**		**480**	

ε beam geometric emittance
ε_1 primary collimator emittance
ε_2 secondary collimator emittance

Correlated painting $\varepsilon_2 > 2\varepsilon_1 > 2\varepsilon$

Anti-correlated painting $\varepsilon_2 > \varepsilon_1 > \varepsilon$

Unit: π mm mrad

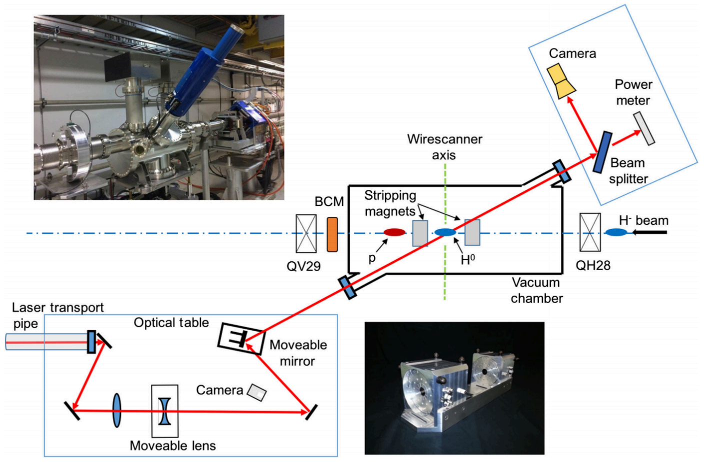


Correlated painting Anti-correlated painting

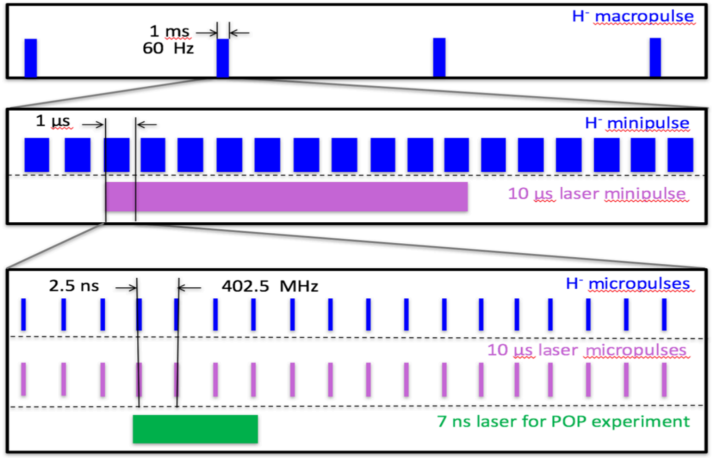
Demonstration of Laser stripping for microsecond H- duration

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

- Reduce the required average laser power by 3 orders of magnitude:
  - Temporal matching of the laser pulse to the H− pulse structure (factor 70)
  - Tailoring of the H− beam trajectories (factor 10)
  - Optimization of H− beam size and divergence (factor 2-5)



- The achieved stripping efficiencies are comparable to the foil-based stripping schemes of about 95% – 98%
- Duration of the laser stripping event is still 2 orders of magnitude below typical millisecond operational pulse lengths (ESSnuSB 2.86/4 ms)
- Possible for millisecond pulse: using cavity to recycle the laser power to reduce the required average laser power



Convergence study