UPPSALA UNIVERSITET

Challenges and status of the ESSnuSB accumulator design

Ye Zou, Uppsala University

On behalf of ESSnuSB accumulator Working Group

16/08/2018

FREIA

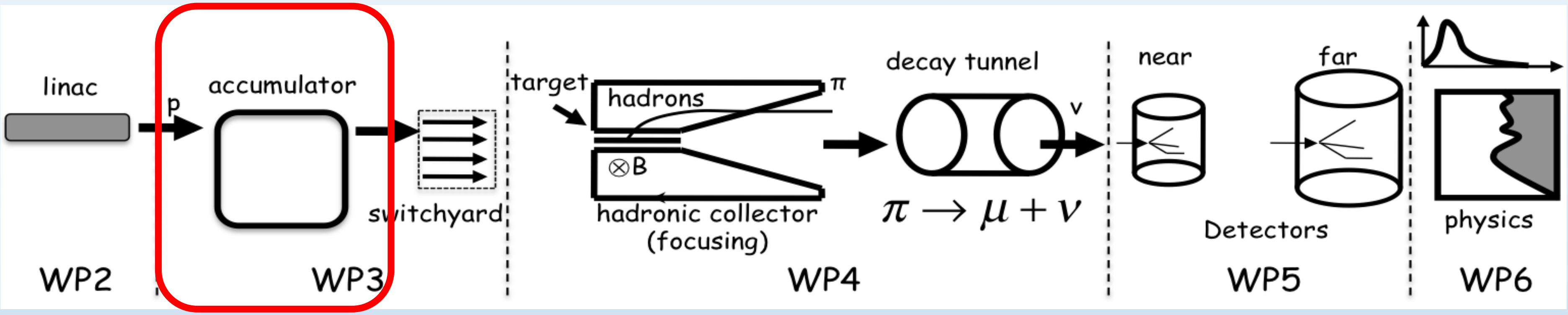
ESS NEUTRINO SUPER BEAM

COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

EuroNuNet

Before the talk

ESSnuSB

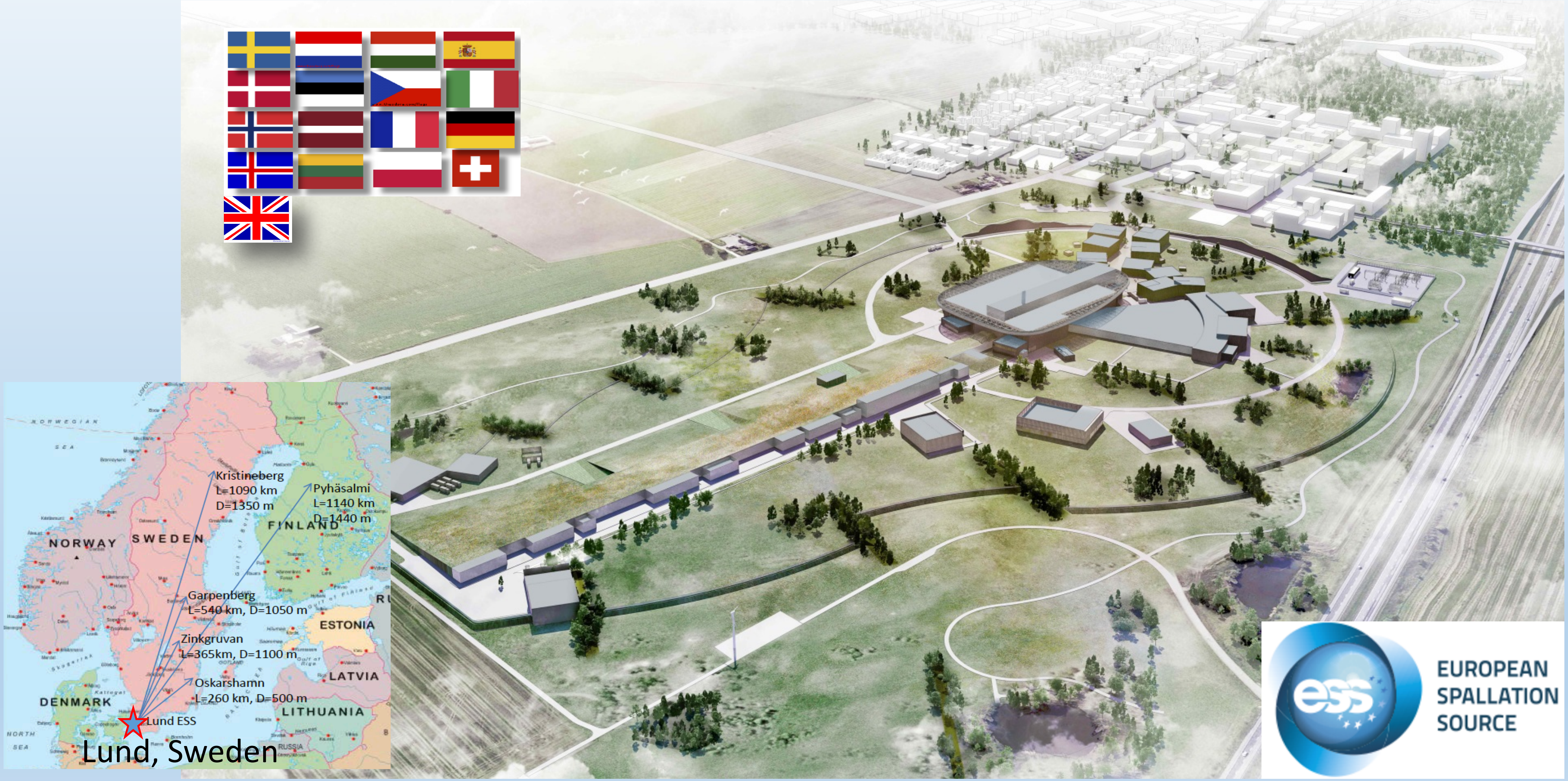


- We have held the 1st ESSnuSB WP3 meeting on June 4th 2018
  http://essnusb.eu/docdbprivate/DisplayMeeting?conferenceid=52

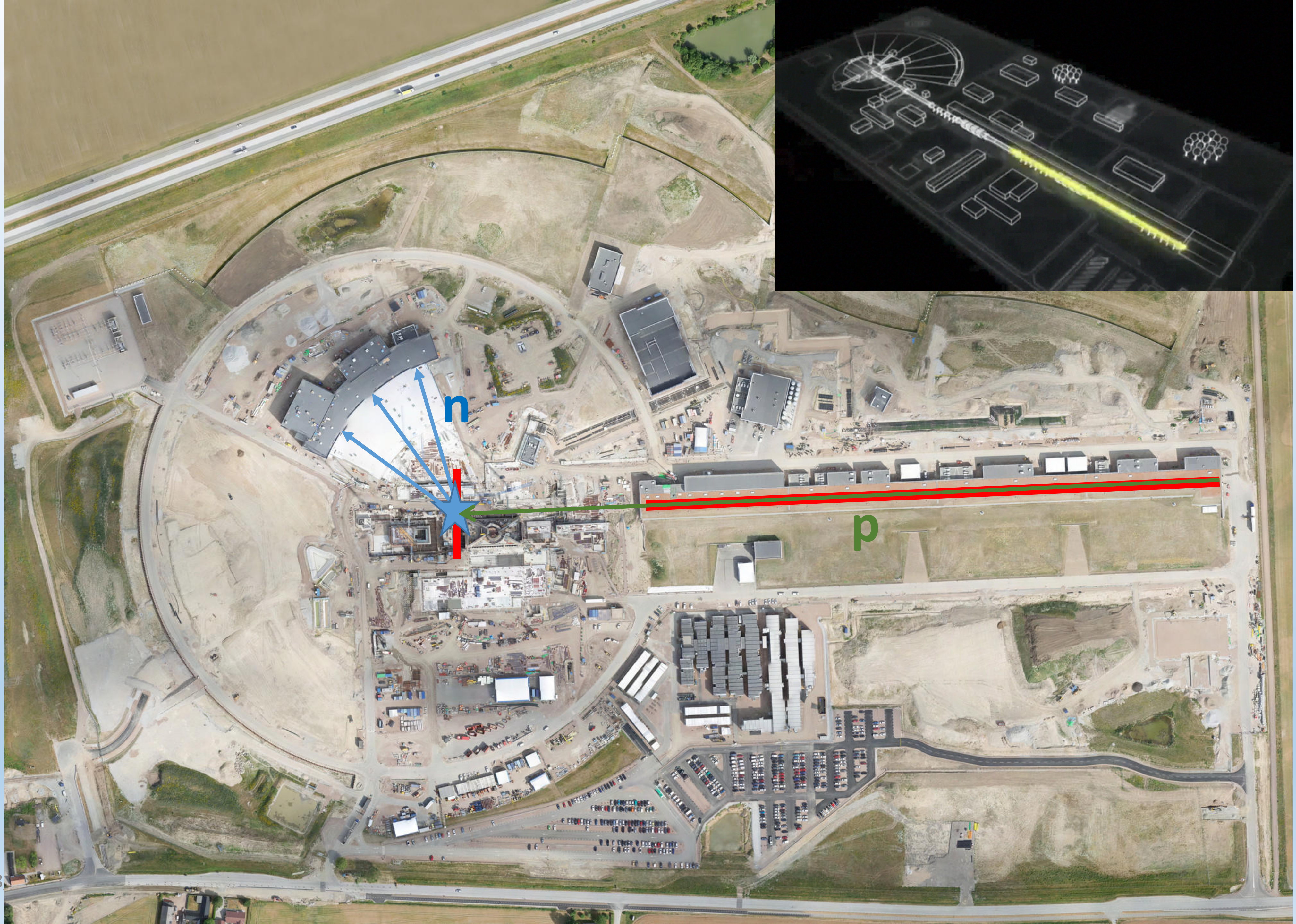
- Accumulator Working Group:

  Elena Wildner, Horst Schönauer (CERN)
  Shinji Machida, Chris Prior (RAL)
  Ben Freemire, Jeffrey Eldred (Fermilab)
  Maya Olvegård, Ye Zou (UU)

The European Spallation Source, ESS



EUROPEAN SPALLATION SOURCE


n
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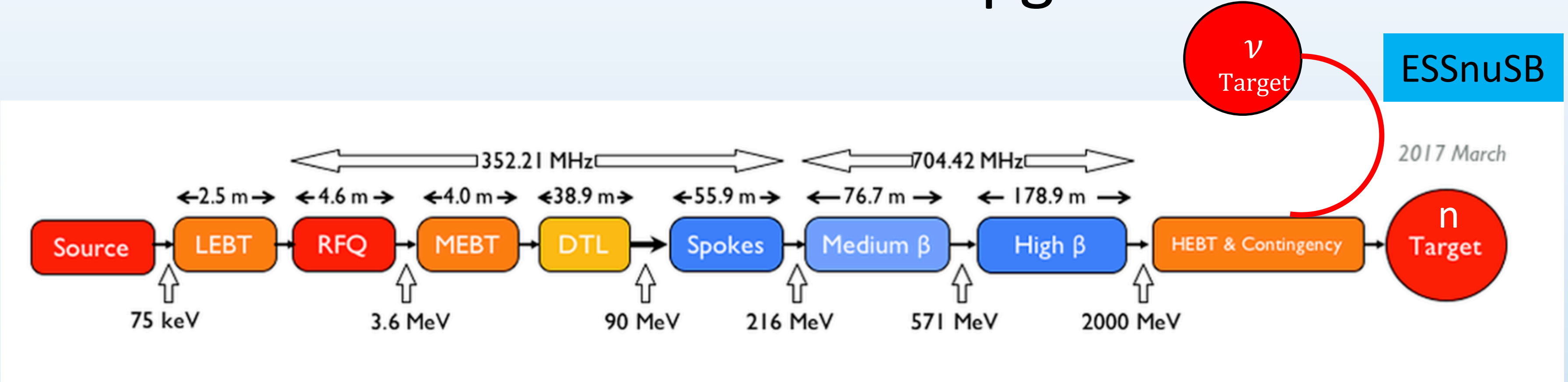
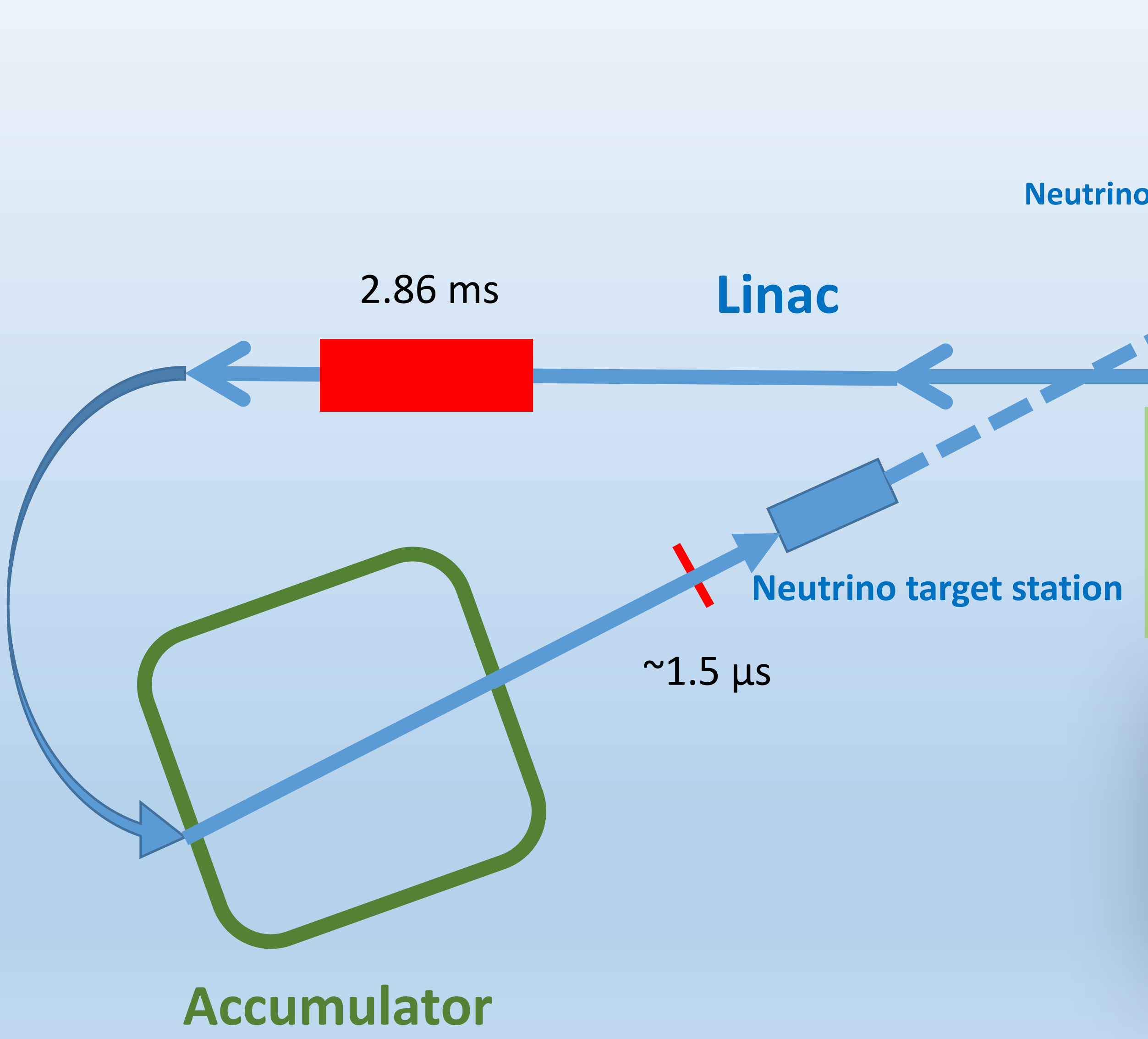
The ESS Linac for neutrons and upgrade for neutrinos



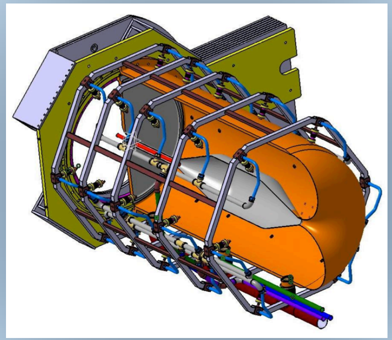
See Björn Gålnander's talk for more details

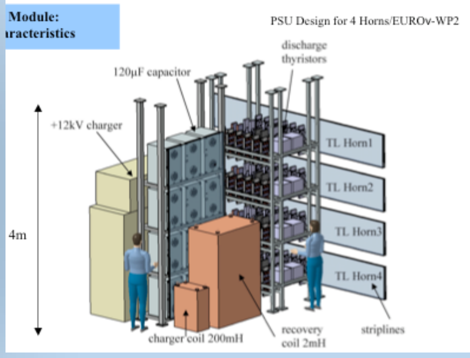
Parameter	Value	Upgrade (n+ν)	Upgrade (n+ν)
Ion species	Proton	Proton + H^-	Proton + H^-
Average beam power	5 MW	10 MW	10 MW
Ion kinetic energy	2 GeV	2 GeV	2.5 GeV
Average macro pulse current	62.5 mA	62.5 mA	50 mA
Average macro pulse length	2.86 ms	>2.86/4 ms	> 2.86/4 ms
Pulse repetition rate	14 Hz	≥ 28 Hz	≥ 28 Hz
Duty cycle	4%	≥ 8%	≥ 8%
Maximum accelerating cavity surface field	45 MV/m	45 MV/m	45 MV/m
Linac length	352.5 m	352.5 m	352.5 + ca 70 m

The mission of the accumulator



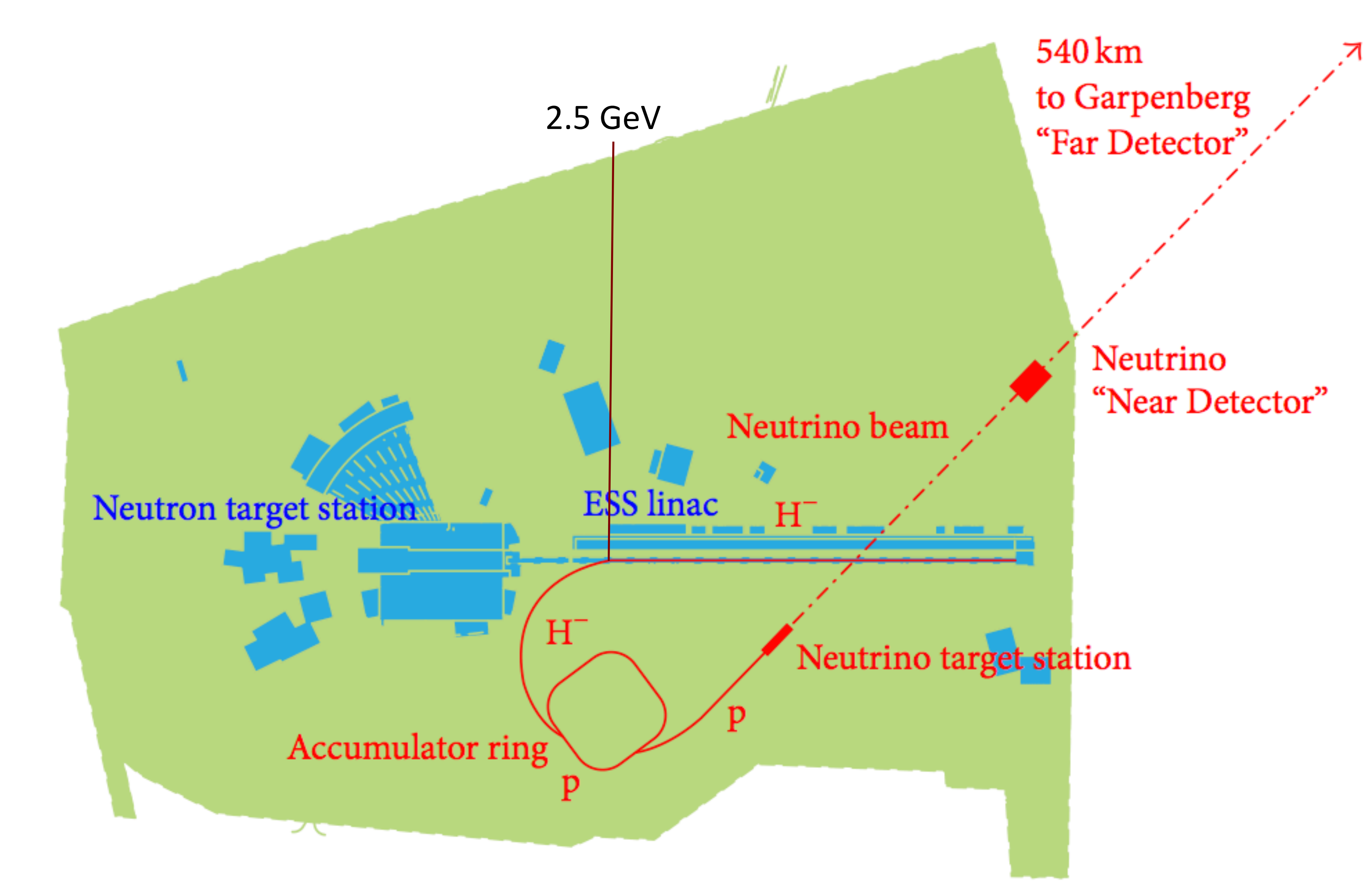
The flat top of the high current pulse of 350 kA in the magnetic horn can not be made longer than about 1.5 μs due to the otherwise excessive ohmic heating





See M. Dracos' talk for more details

The ESSnuSB baseline layout on the ESS site



Challenges of the ESSnuSB accumulator

Challenges of the ESSnuSB accumulator

- To design an accumulator which can accommodate 5 MW average beam power, the primary concern is the radioactivation caused by excessive uncontrolled beam loss, which can limit a machine's availability and maintainability
- Based on SNS experiences, hands-on maintenance demands average uncontrolled beam loss: 1 W/m
- For 5 MW power, a fractional beam loss of 2×10^{-7} per meter required; for an accumulator several hundred meters in circumference, total uncontrolled beam loss must be lower than 10^{-4}

Uncontrolled beam loss usually attributed to:

- A high space charge tune shift (> 0.25) at injection
- Beam injection: not fully stripped H^- and H^0 and electrons and injection foil scattering
- Limited transverse and momentum acceptance
- Instabilities
- …

Space-charge tune shift

Space-charge tune shift
$$\Delta Q_{x,y} = -\frac{r_0 N}{2\pi E_{x,y}\beta^2\gamma^3 Bf}$$

N: 1.1×10^{15}

$E_{x,y}$: 75 π mm mrad

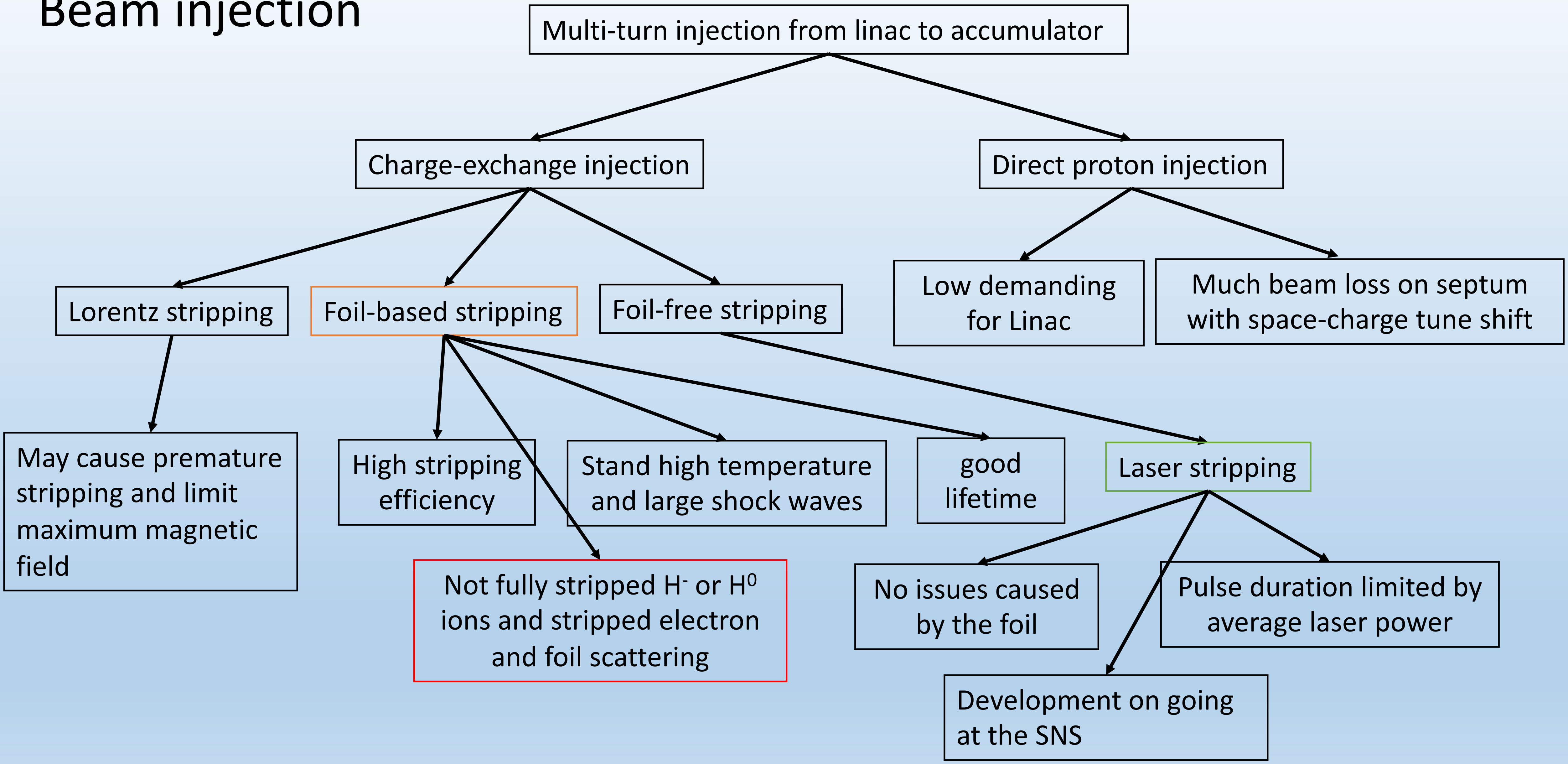
$\beta^2\gamma^3$: 27.58

Bf: 0.4

r_0	Classical radius
N	Beam intensity
$E_{x,y}$	Transverse emittance
$\beta\gamma$	Relativistic factors
Bf	Bunching factor

- 1.1×10^{15} circulating protons in a ring with circumference corresponding to about 1.5 μs would result in tune shifts of 0.32 – 0.64 (too high)
- Space-charge tune shift requirements: < 0.2
- To address it, total beam intensity for one filling should be reduced to 1/3 or 1/4 considering the worst case

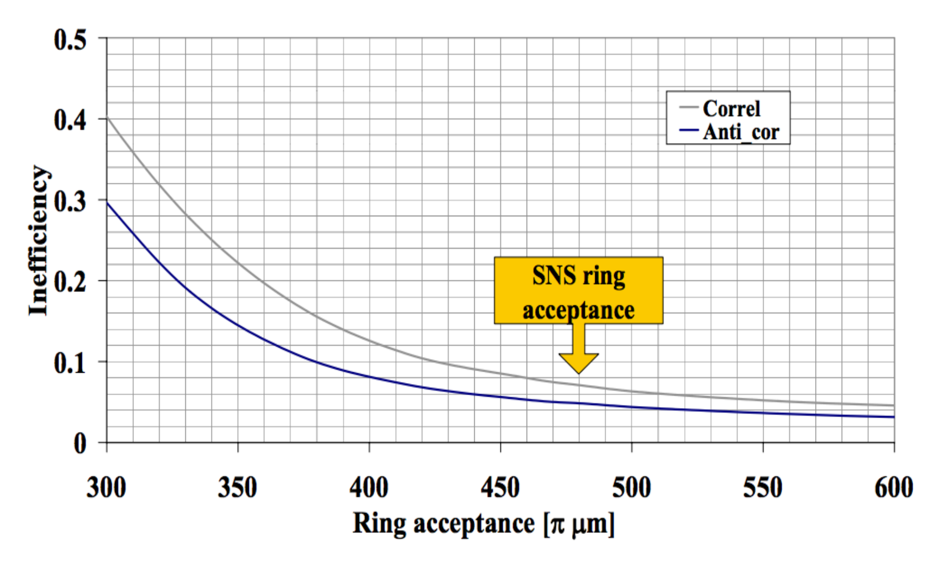
Beam injection



Beam collimation and acceptance

- Localize the controllable beam loss
- Modern collimation system usually adopts two-stage design: primary collimator as a scrapper scatter the halo particles and secondary collimators collect them
- Supposing beam halo contains 10^{-3} of the total particles, the design collimation efficiency must be higher than 95%
- Sufficient transverse and momentum acceptance for efficient beam collimation

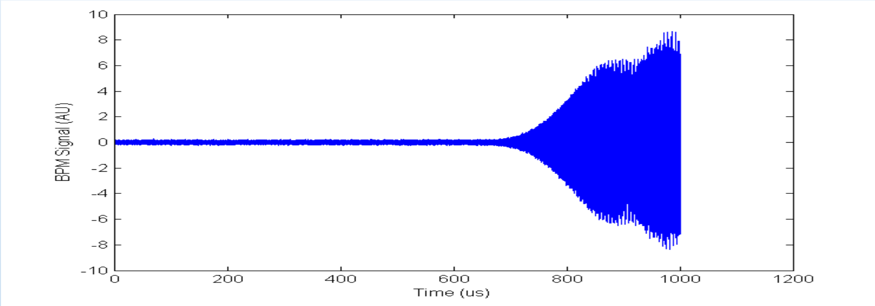
N. Catalan-Lasheras

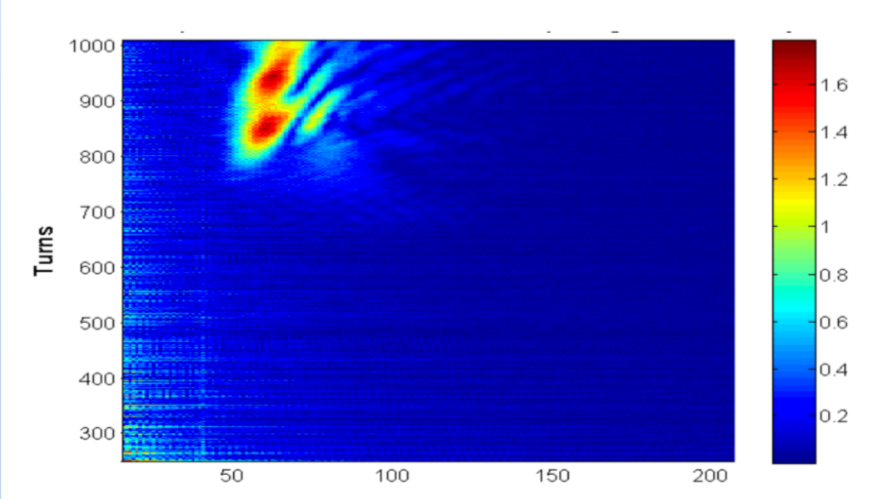


Instabilities

S. Cousineau

- For the accumulation period of about 1 ms, main instability is e-p instability
- A broadband phenomenon due to the interaction of a proton beam with a cloud of electrons in the vacuum chamber
- May cause emittance growth, beam loss, and significant pulse-to-pulse variation in beam motion
- First observed in the PSR, well considered in the SNS design
- Mitigation measures:
  - A large aperture (≥10 cm beam pipe radius) to reduce beam losses that lead to electron build up
  - Special vacuum vessel coating (TiN) to reduce secondary emission yield



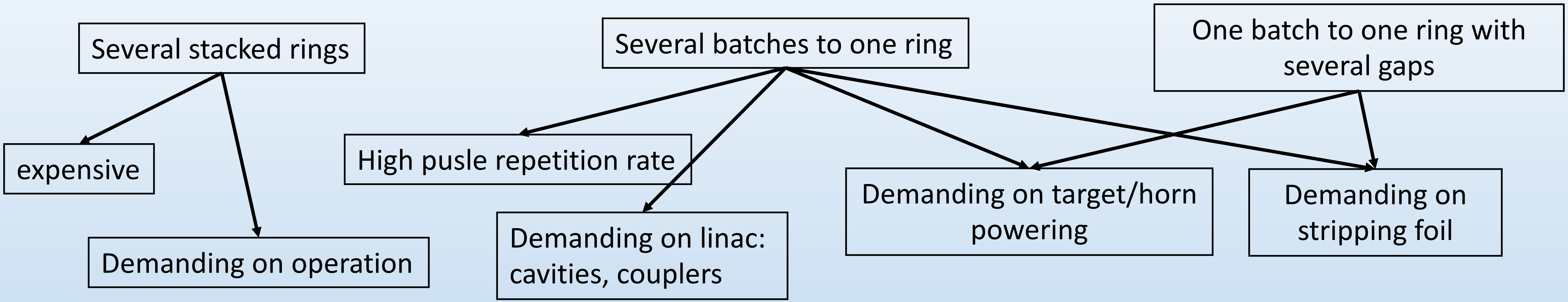


Other challenges

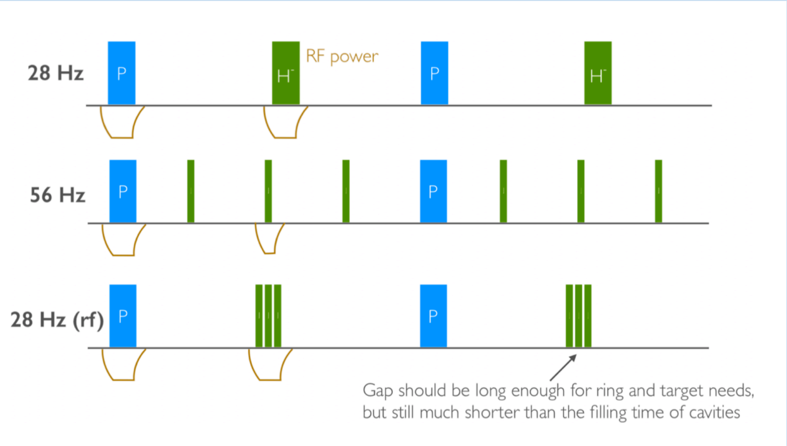
- Beam gap for extraction
  - About 100 ns beam gap is needed for the extraction kicker rise-time
  - Chopper in the linac or barrier bucket RF in the ring
- From the ESS linac
  - H^- source to be added, accelerate proton and H^- pulse interleaved
  - High average power: from 5 MW to 10 MW, a big step
  - Linac equipment to be adapted
- From transport line
  - Beam loss from Lorentz stripping (site layout has taken this into account)

Preliminary design of the ESSnuSB accumulator

Beam pulse structure schemes



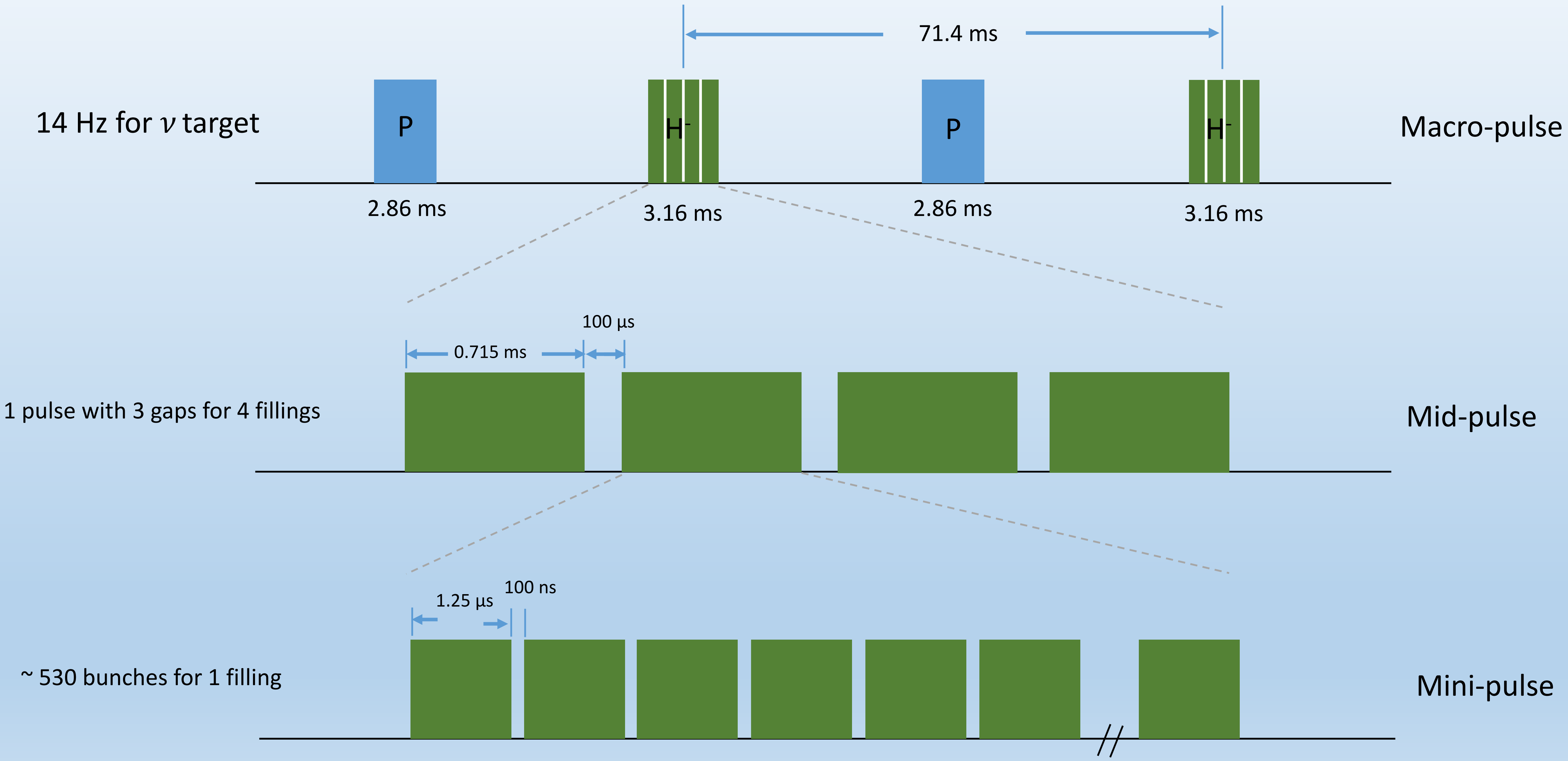
	1 Ring 1B L	1 Ring 3B F	3 Ring 1B F	1 Ring 1B P	3 Ring 3B P
Number of rings	1	1	3	1	3
Linac beam batches	1	3	1	1	3
Linac Pulsing [Hz]	28	56	28	28	56
Pulse length [ms]	> 2.86	> 2.86/3	> 2.86	> 2.86	> 2.86/3
Extr. chopping [ns]	100	100	100	100	100
Inj. chopping [μs]	100	na	>100	100	na
Inj. stripping	laser	foil	foil	na	na



B: Batches
L: Laser stripping
F: Foil stripping
P: Proton injection

E. Wildner

Baseline beam pulse structure



H^- foil-stripping injection

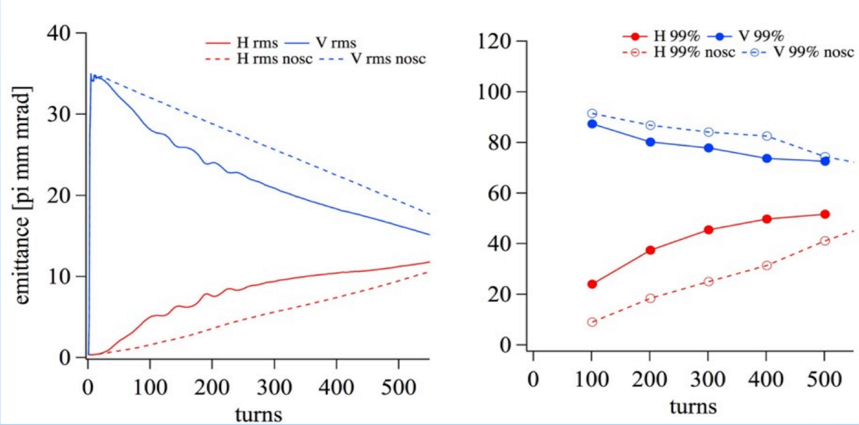
M. Olvegård

With J-PARC like lattice

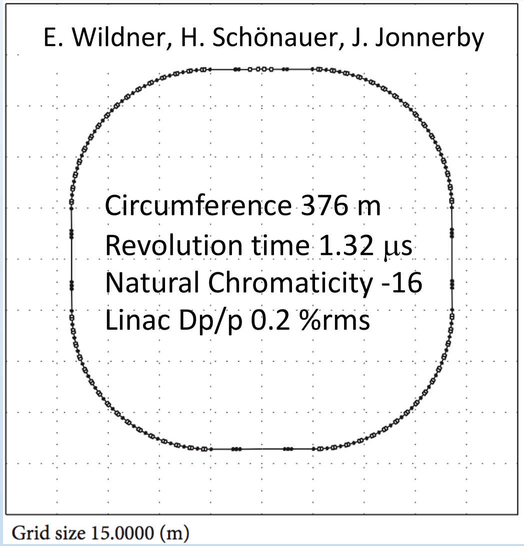
S. Machida

Anti-correlated painting

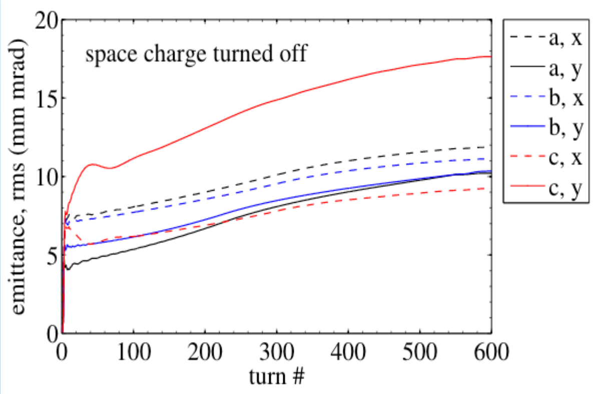
circumference	348.333 m
superperiod	3
tune	6.4, 6.4
gamma-t	9.7
max energy	3 GeV

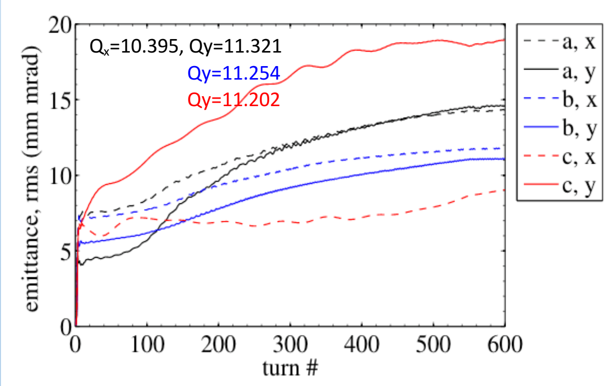


With the old ESSnuSB lattice



- With correlated painting
- With and without space charge
- 15 % gap for extraction





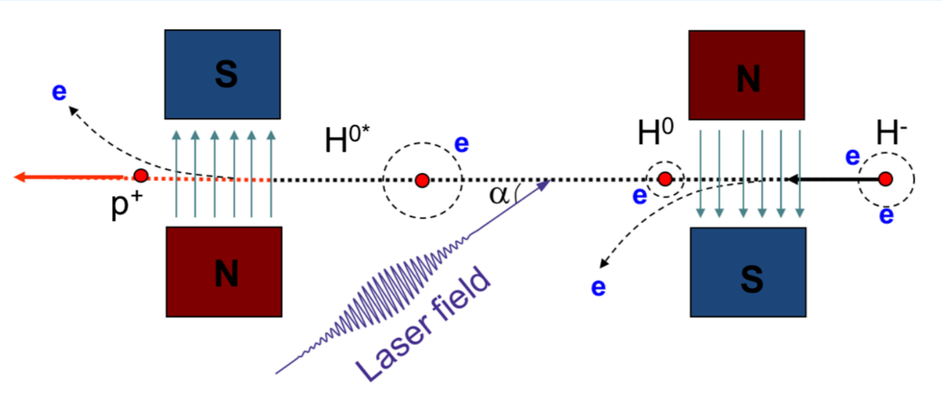
First simulations (multi-turn injection with correlated and anti-correlated painting) show no worrying space charge at 2 GeV

laser stripping

- So far, laser stripping is the most promising foil-free alternative stripping scheme
- Latest demonstration of laser stripping for microsecond pulse (11 μs) at SNS (stripping efficiency comparable with foil-based stripping) Sarah Cousineau et al., PRL 118, 074801 (2017)
- How to reduce the required average laser power is the key issue for longer pulse
- Possible for millisecond pulse: using cavity to recycle the laser power

Laser stripping scheme

Sarah Cousineau



Lorentz stripping of the first electron by a dipole magnet in the first step, resonant excitation of the second electron by the laser in the second step, and, finally, stripping of the excited electron by the second dipole magnet

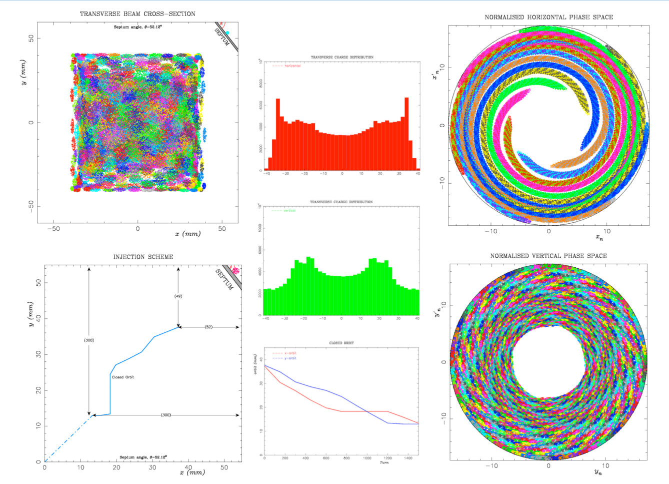
Direct proton injection

Courtesy Chris Prior

- Direct proton injection using a tilted electrostatic septum.
- Builds on ideas developed for HIDIF fusion studies (Prior, 1998)
- Higher currents are available for a proton linac *cf* H^-.
- Simple bump magnet injection chicane (H & V).
- No complications with stripping foils, H^0 excited states, stripped electrons etc.
- A similar scheme is being studied for a new UK spallation neutron source, the Chinese heavy ion facility (HIAF) and for FAIR at GSI.

Parameter	Main Ring
Kinetic energy at injection (GeV)	2.0
Repetition rate (Hz)	14
Number of ions $N(\times 10^{15})$ (5 MW)	1.1/4
Linac beam current (mA)	62.5
1σ normalised injected emittances (π mm.mrad)	0.25
3σ unnorm. linac emittances (π mm.mrad)	0.758
Painted H&V ring emittances (π mm.mrad)	?
Number of ions $N(\times 10^{14})$ (5 MW)	11.14
Ring circumference (m)	376
Revolution period at injection, t (μs)	1.32

Space charge effect not considered



Total beam loss =0.00 %
(assuming uniform beam)

EQUATION OF SEPTUM $ax + by + c = 0$, with

$a = 0.789315, b = 0.613989, c = -72.757873$ (x and y in mm)

Septum angle $\theta = 52.12°$

Ring acceptance $\mathcal{A} = 480\,\pi$ mm.mrad

Space charge effect considered

ISIS RCS INJECTION WITH SPACE-CHARGE

- Uses CRP-code Track2d, linear lattice with 2H/V kickers out, 2 in for injection orbit bumps.
- KV input beam from linac.
- Simulation with full non-linear space charge
- Model indicated zero beam loss in the absence of space-charge.
- Tracking gave beam loss of ~ 17%
  - clear opportunities to improve scheme by modifying orbit bumps to allow for tune shift.
  - iterative optimising process.

Collimator and ring acceptance

	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

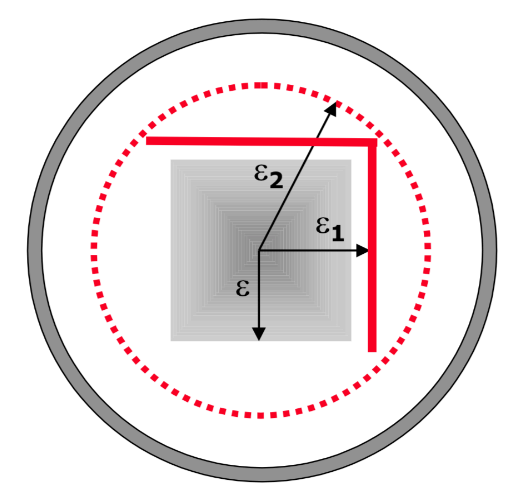
ε_1 primary collimator emittance

ε_2 secondary collimator emittance

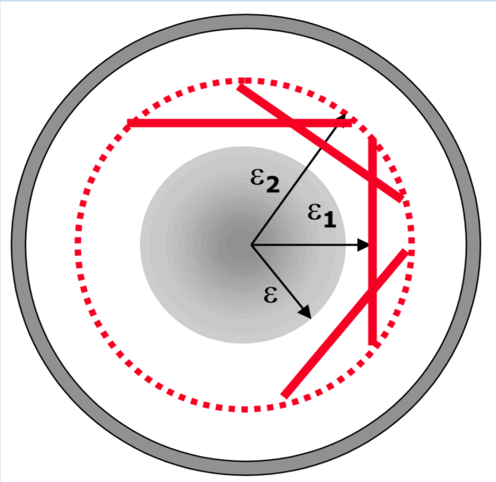
Correlated painting $\varepsilon_2 > 2\varepsilon_1 > 2\varepsilon$

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

Unit: π mm mrad



Correlated painting

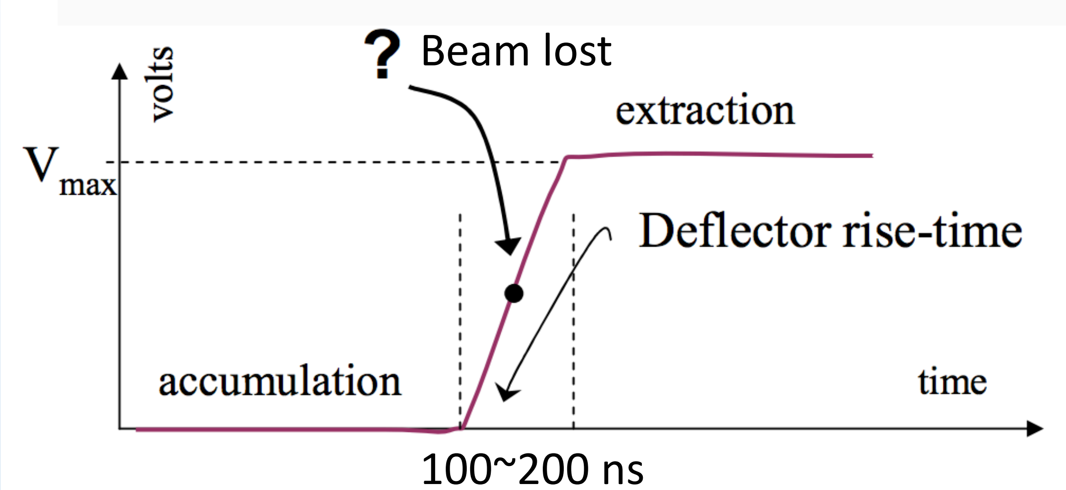


Anti-correlated painting

Beam extraction

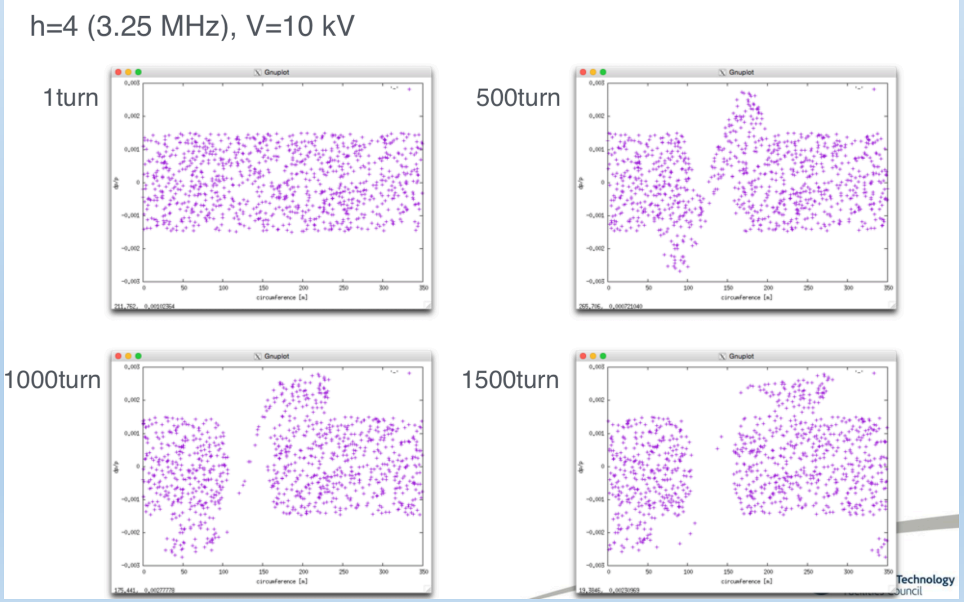
A. Aleksandrov

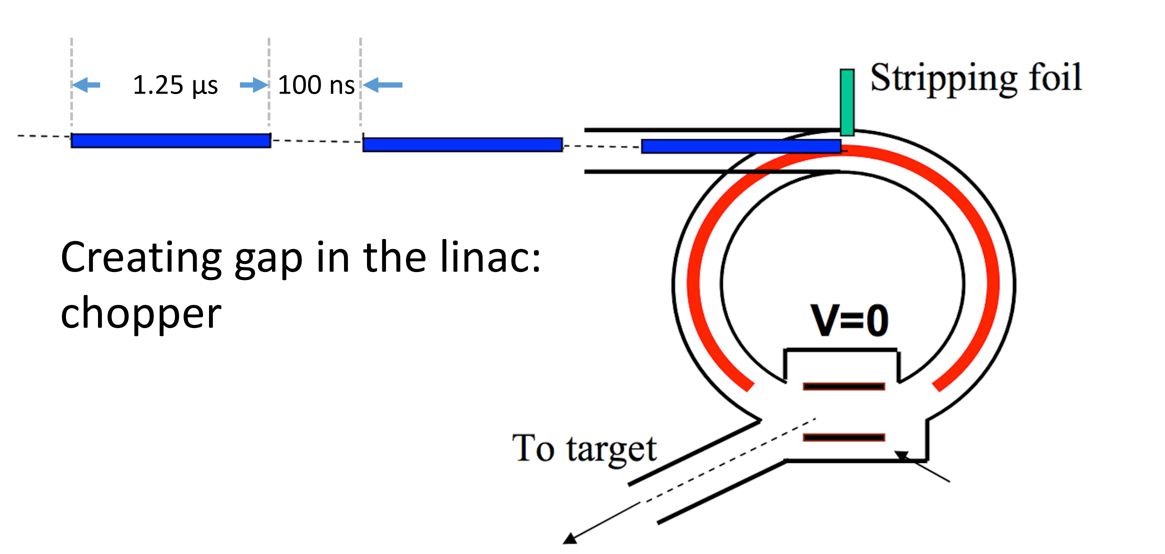
- Single turn extraction
- Gap needed for the extraction kicker rise-time
- Created in the linac and maintained by RF bucket in the ring or created in the ring using barrier bucket
  - Chopper in the linac: more straightforward, but may cause HOM problem (now under study)
  - Barrier bucket RF: many turns needed after injection



Creating gap in the ring: Barrier bucket

S. Machida

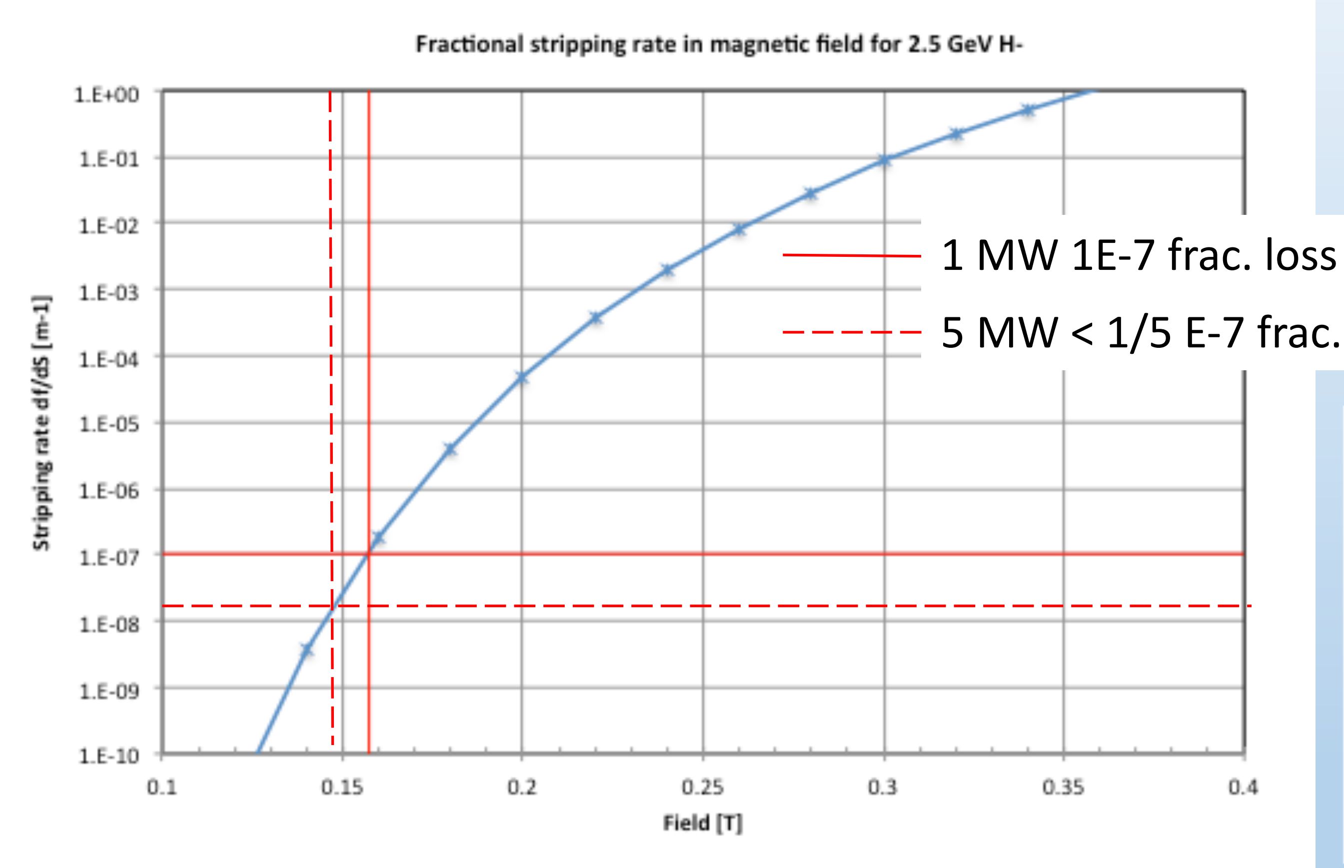


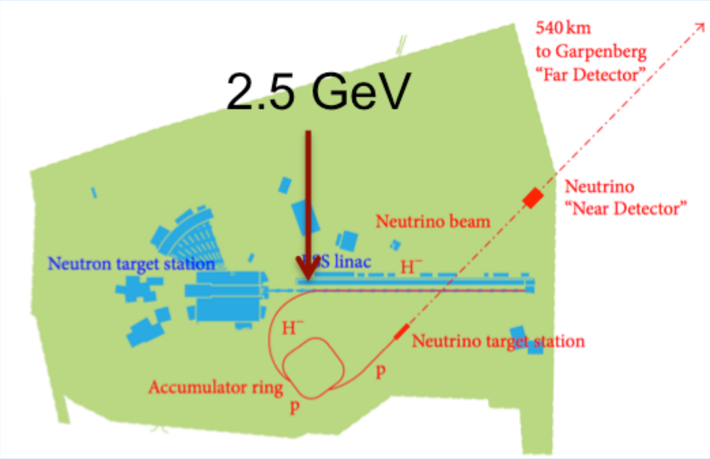


H^- Transfer Line: stripping rates

E. Wildner

- The Lorentz stripping gives a practical limit of the energy/bending of the transfer line





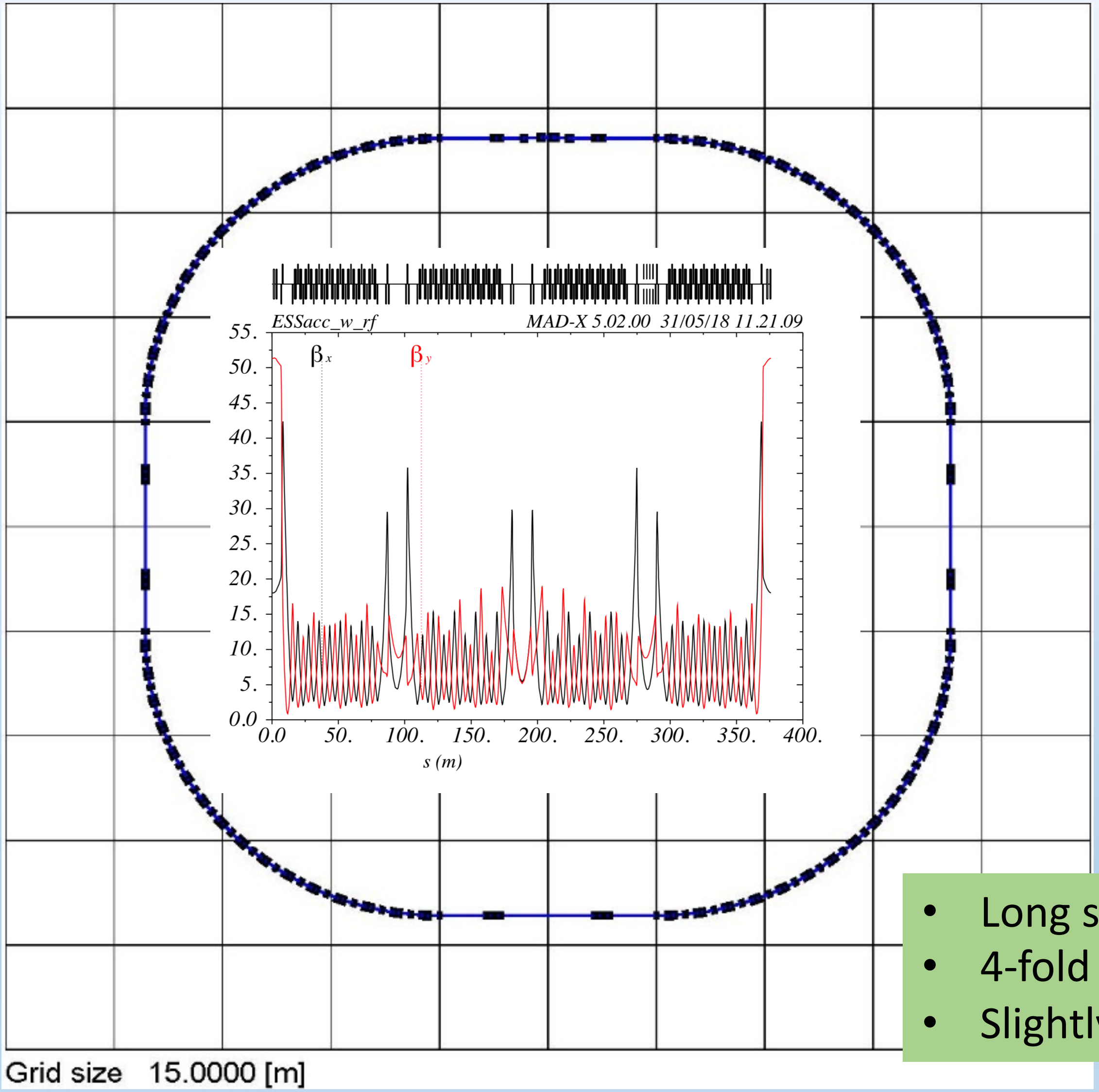
0.15 T and 2.5 GeV: $B\rho$=11.02 Tm, ρ=73.5 m in dipoles

66% dipole filling factor, transfer line tunnel ρ=111 m

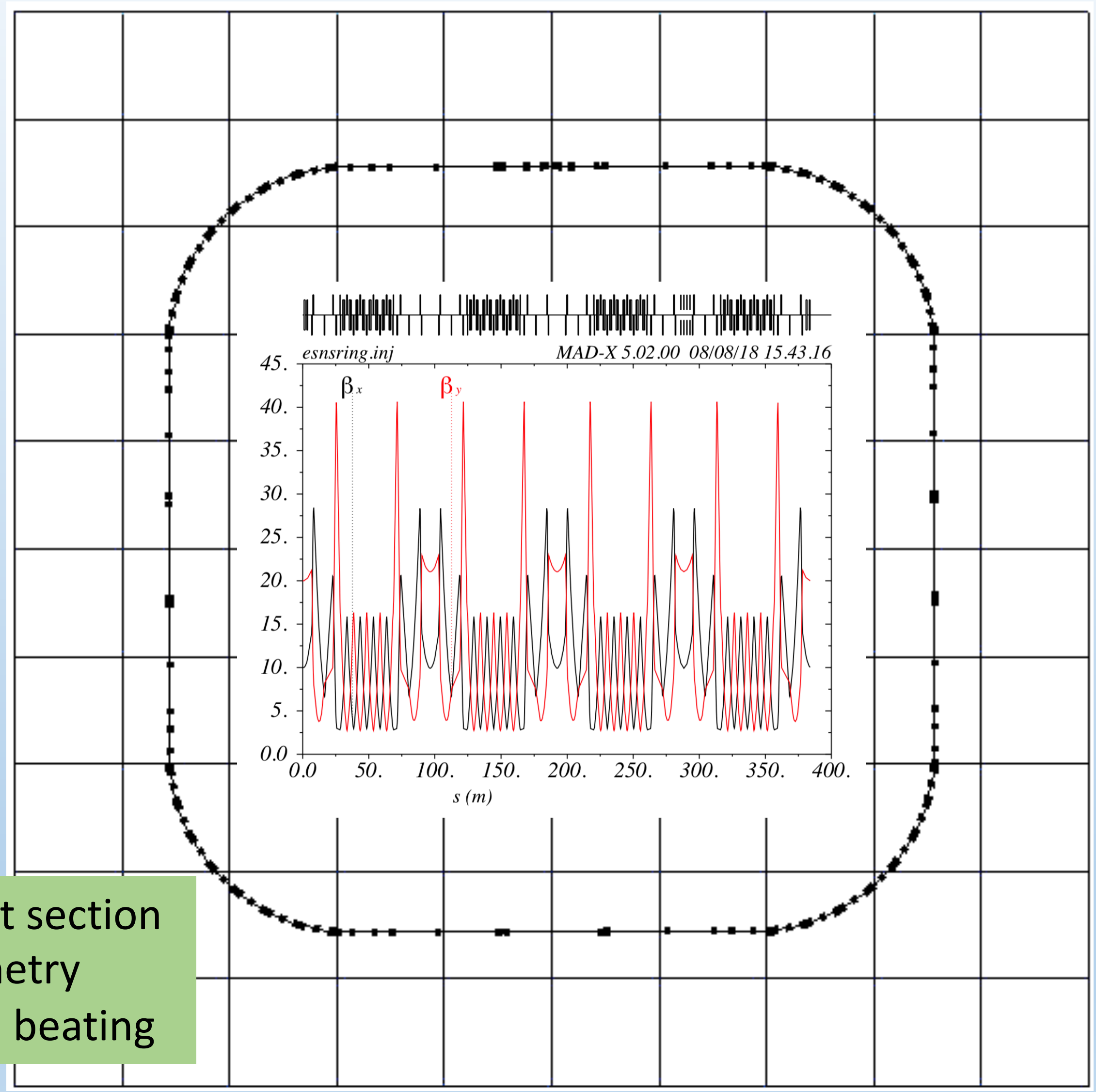
Preliminary results with the current lattice

The lattice development

Horst Schönauer



- Long straight section
- 4-fold symmetry
- Slightly beta beating



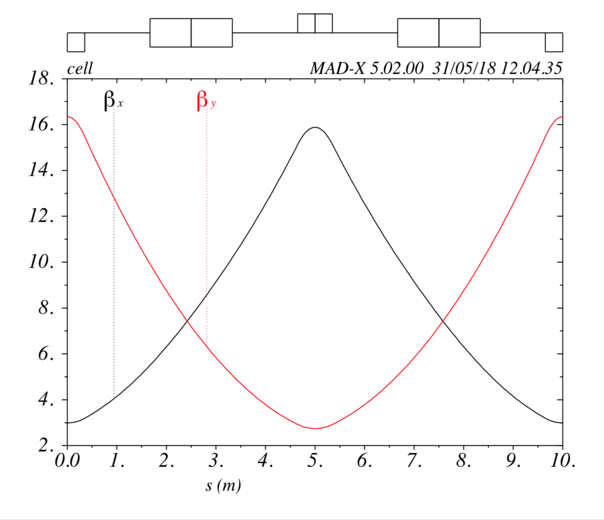
Lattice 15/16

Lattice 17/18

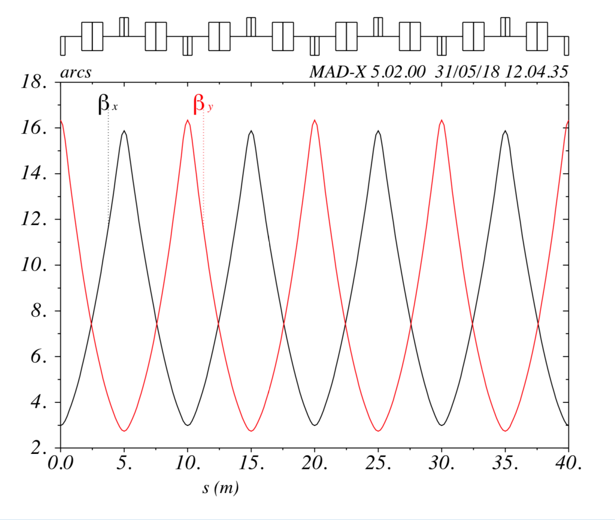
The lattice development

- Circumference: 384 m
- Four-fold symmetry
- 4 Arc + 4 Straight sections
- Arc : 4 FODO cell, 4×10 m
- Straight: 56 m
- Slightly beta beating due to the bump

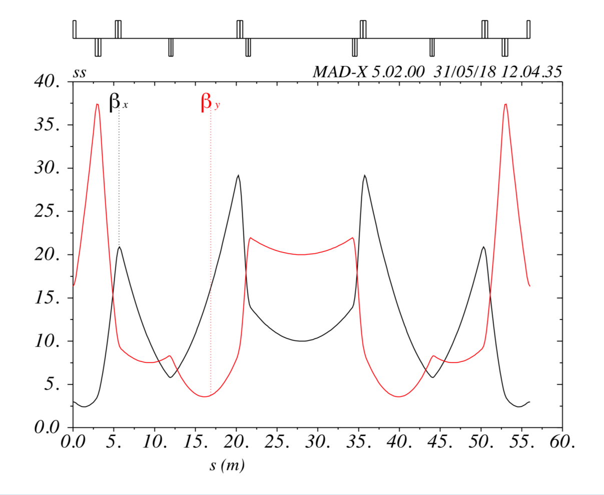
Cell



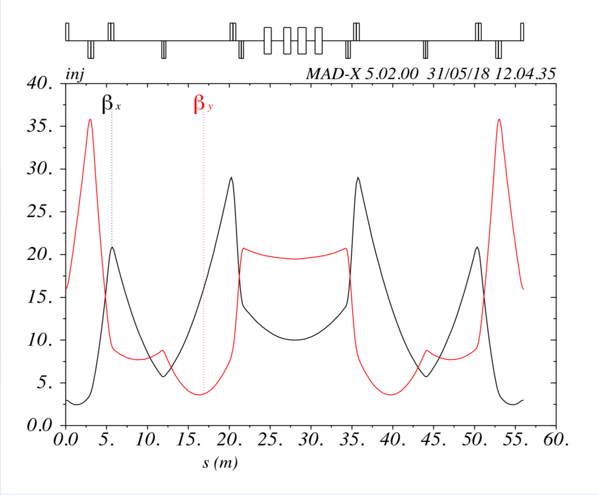
ARC



Straight



Injection



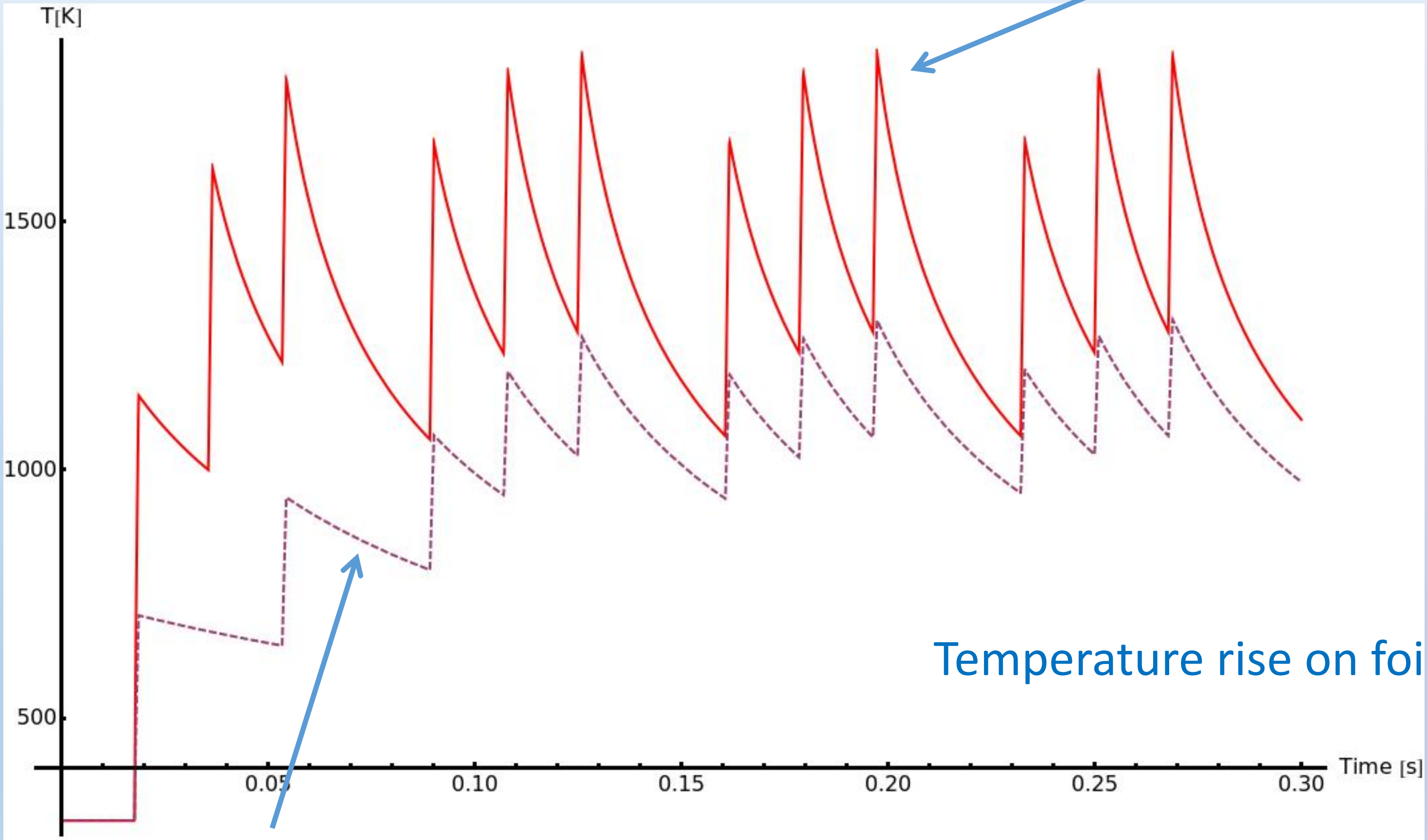
Parameter	Value	Unit
Circumference	384.01	m
Average radius	61.12	m
Injection/Extraction Energy	2/2	GeV
Beam power	5	MW
Repetition rate per ring	14	Hz
Number of protons	1.1	10^{15}
Ring dipole field	1.0945	T
Magnetic rigidity, $B\rho$	9.2877	T m
rf harmonics	1,2	
Peak rf voltage, h = 1/2	5/2.5	kV
Un-normalized emittance hor. or ver.	75-100	π mm mrad
Collimator acceptance	200-260	π mm mrad
Betatron acceptance	400	π mm mrad
Max beta hor./ver.	28.86/37.33	m
Horizontal Tune	8.2-8.3	
Vertical Tune	8.3-8.4	
Transition energy, γ_T	5.82	GeV
Horizontal natural chromaticity	-11.35	
Vertical natural chromaticity	-12.87	
Number of superperiods	4	

Temperature on foil with new lattice

Horst Schönauer

Combined linac spot and circulating beam

3 batches from Linac



Not yet optimized

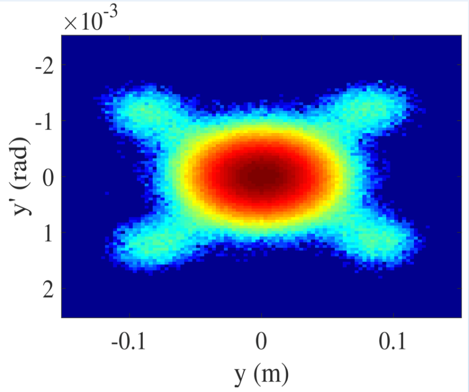
Temperature rise on foil seems acceptable

Linac spot

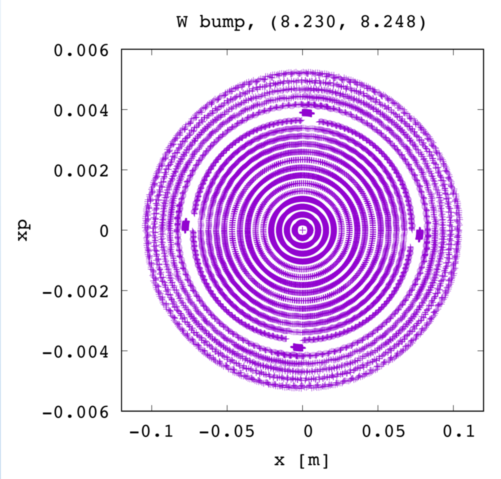
SIMPSONS tracking without space charge

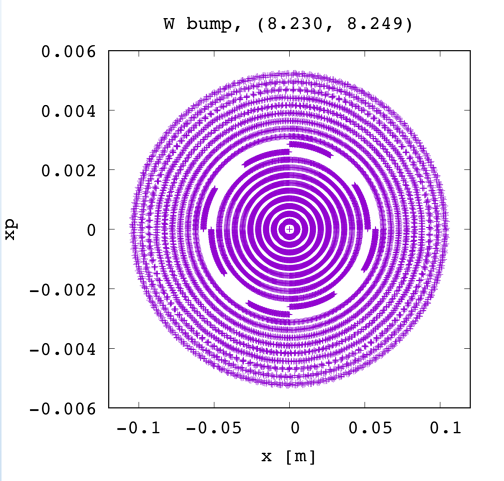
Shinji Machida

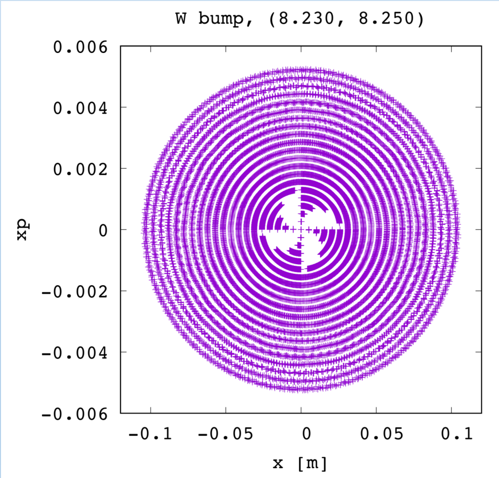
Fourth-order resonance was observed with the 2015/16 version lattice in the vertical plane when Qy=11.248 without space charge

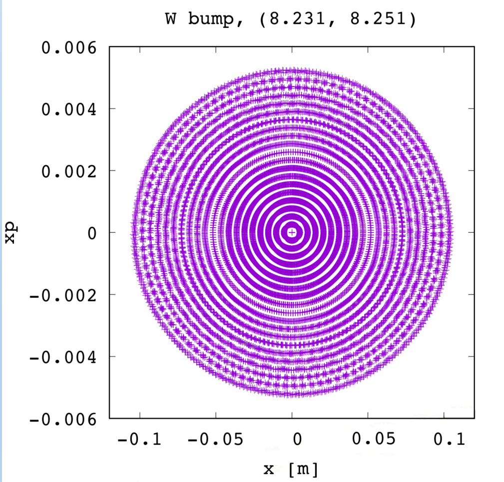


M. Olvegård







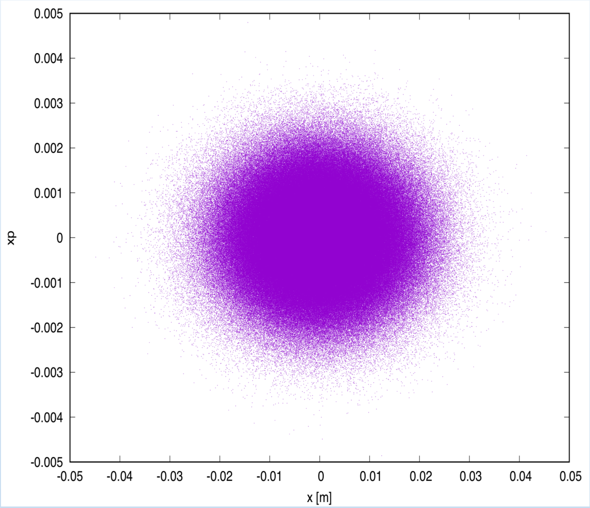


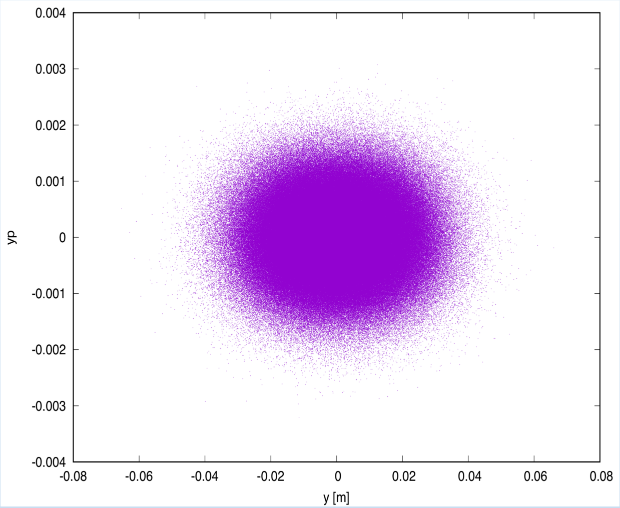
- Results show a Poincare map of 1000 turns
- No space charge is included
- Tune is adjusted by only qf and qd in arc, keeping the other quadrupole strength the same
- Scan vertical tune around quarter integer (8.250) and see any resonances in phase space comes out. Horizontal tune is fixed (almost)

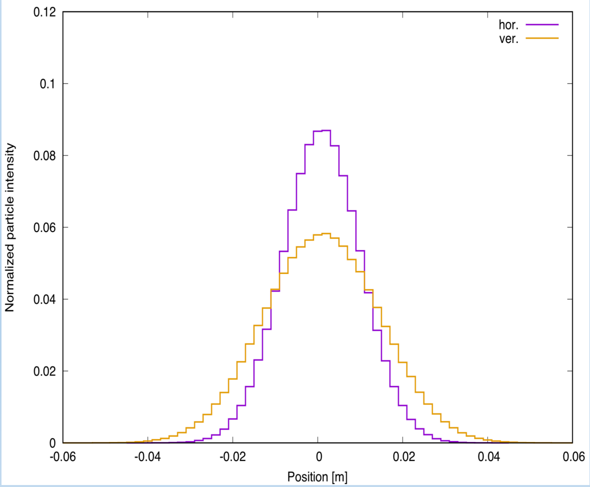
- Amplitude dependent tune shift is noticeable
- It is not a resonance islands, it simply shows the tune is exactly 8.250 at that particular amplitude
- New lattice does not show quarter integer resonance islands which was a concern of the old lattice

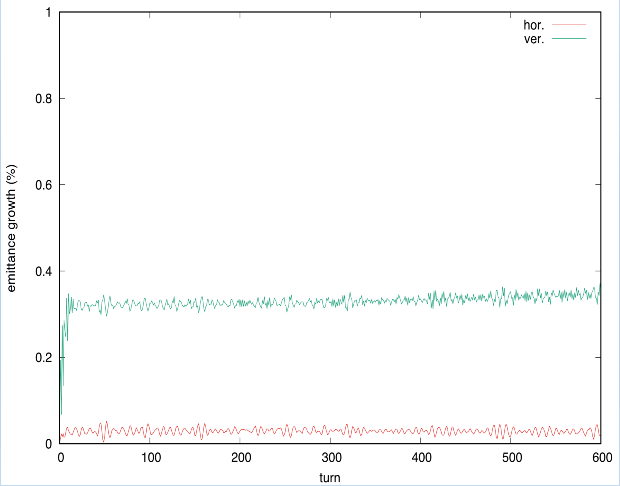
Multi-particle simulation: full injection

- Full intensity injection to see emittance evolution
- Current lattice ($\nu_x = 8.27, \nu_y = 8.34$)
- 10^6 particles with 1 σ normalized emittance of 100 mm mrad (Gaussian) as required by target
- 15 % gap for extraction
- 550 turns (with full intensity)
- PyORBIT (including PTC external libraries)
- Very small emittance growth





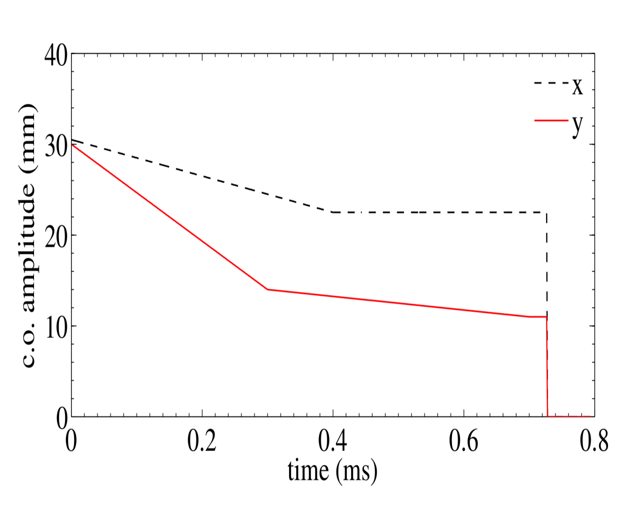


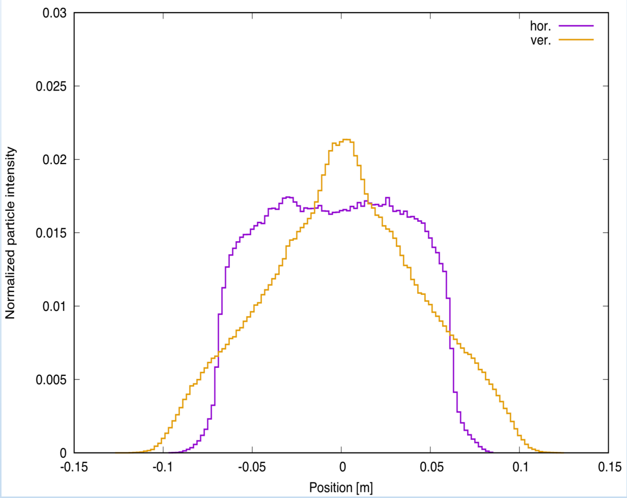


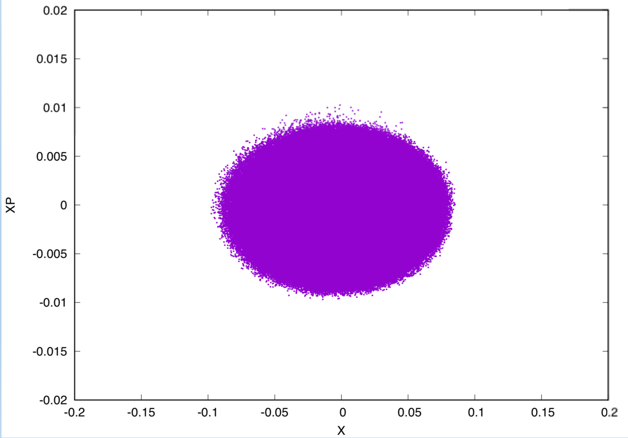
Multi-particle simulation: injection painting

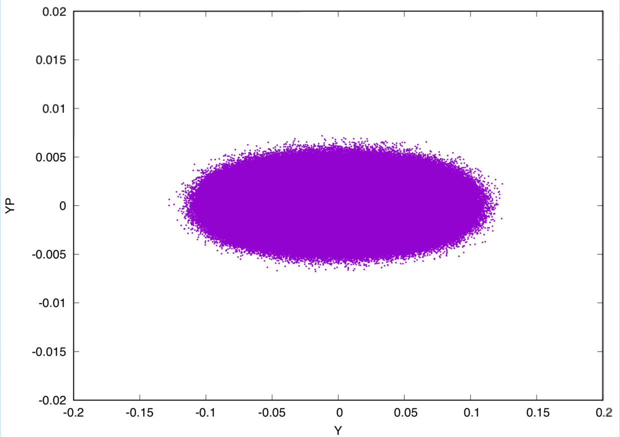
- First try injection painting
- New Lattice ($\nu_x = 8.27, \nu_y = 8.34$)
- Bump function not optimized
- Inject 550 turns with 2000 particles per turn, total 1.1 million
- Injected beam normalized emittance from linac: 0.25 πmm mrad
- Correlated painting
- Longitudinal distribution: uniform in z and 1D Gaussion in energy, with max dispersion 1%
- Space charge included

▪ Beam profile in vertical plane is not so flat
▪ The closed orbit bump (c.o.) function need to be optimized
▪ Anti-correlated injection scheme will be performed later









Conclusions and next work

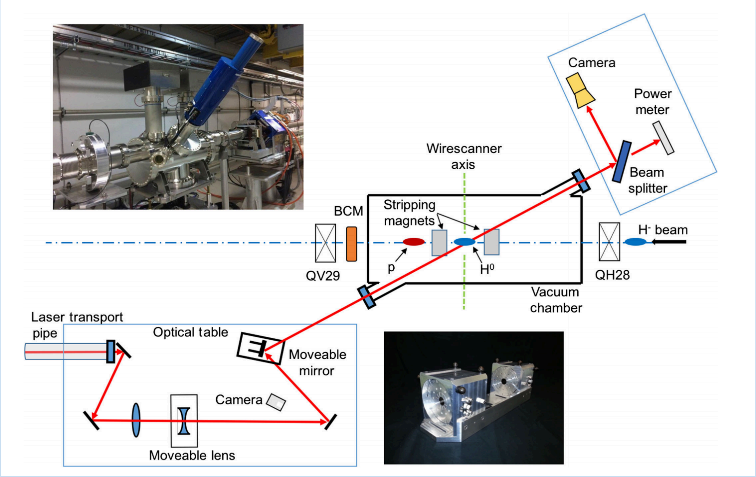
- ✓ Linac upgrades for the ESSnuSB possible to implement
- ✓ First design has been performed
  - ✓ 1 ring, based on SNS experience, 3 batches, 56Hz, foil stripping
- ✓ New baseline
  - ✓ 1 ring, 1 batch, 100 μs gap, laser stripping, requiring lattice modification
- ✓ Optics: new design lattice, 4 fold, longer straight section, no resonance close to 4-order resonance
  - ✓ Temperature on foil seems ok
  - ▪ Lattice to modify for laser stripping injection
  - ▪ Beam dynamics to check beam loss and beam properties
- ✓ First simulation results
  - ▪ Painting scheme to be optimized
- ▪ Collimation to be designed, radiation studies an important issue

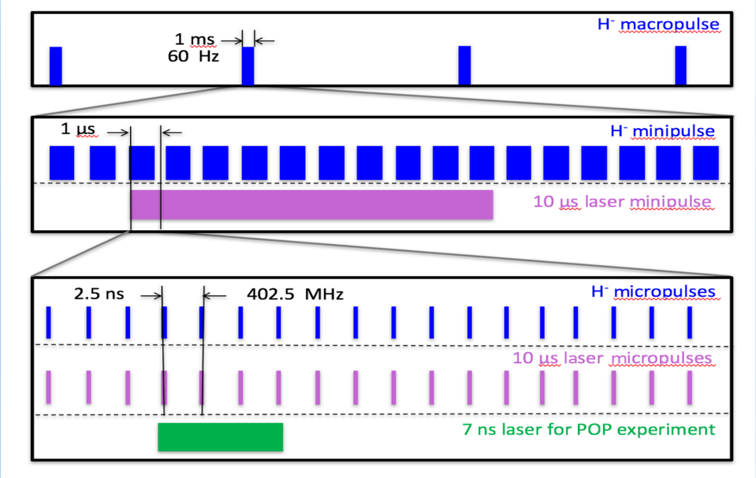
Extra slides

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

Emittances in Accumulator

Table I: Fractional emittance for Gaussian distribution. Un-normalised 99% emittance of 75 mm mrad is assumed first.

beam size	fraction	Emittance (un-nor.)	Emittance (nor.)
3 sigma	98.9%	**75** mm mrad	225 mm mrad
2 sigma	86.5%	33 mm mrad	100 mm mrad
1 sigma (rms)	39.3%	8.3 mm mrad	25 mm mrad

Table II: Fractional emittance for KV distribution. Un-normalised 100% emittance of 75 mm mrad is assumed first.

beam size	fraction	Emittance (un-nor.)	Emittance (nor.)
2 sigma	100%	**75** mm mrad	225 mm mrad
1 sigma (rms)	25%	19 mm mrad	56 mm mrad