



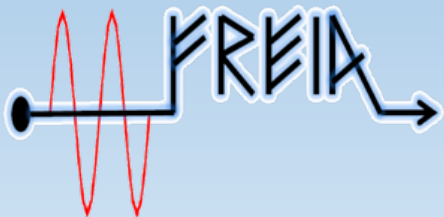
UPPSALA
UNIVERSITET

Challenges and status of the ESSnuSB accumulator design

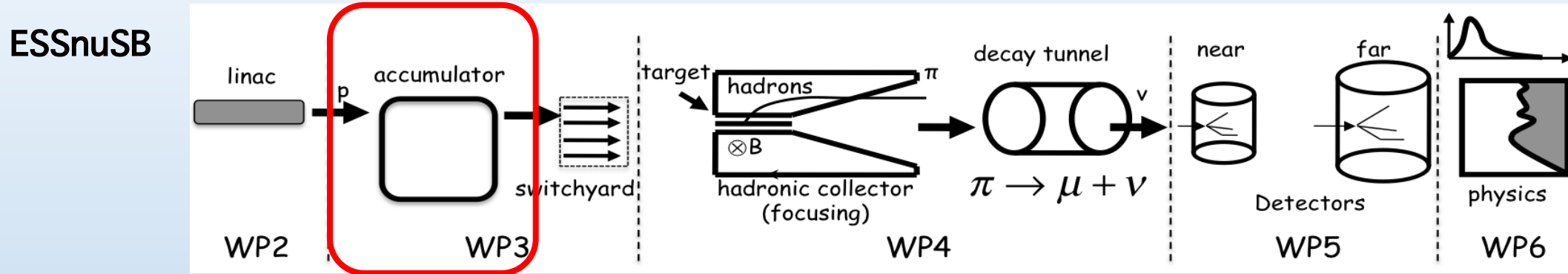
Ye Zou, Uppsala University

On behalf of ESSnuSB accumulator Working Group

16/08/2018



Before the talk



- We have held the 1st ESSnuSB WP3 meeting on June 4th 2018

<http://essnusb.eu/docdbprivate/DisplayMeeting?conferenceid=52>

- Accumulator Working Group:

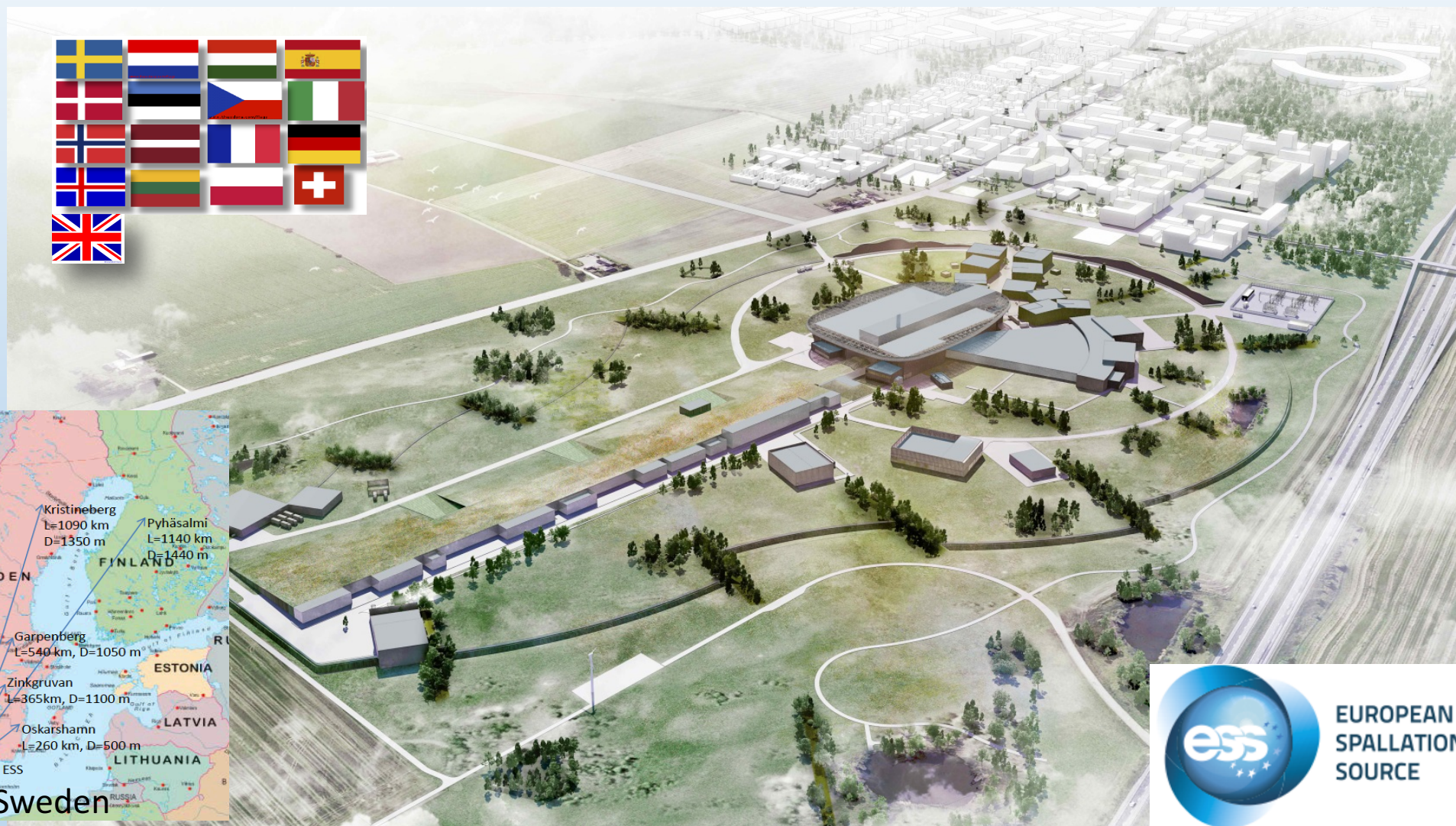
Elena Wildner, Horst Schönauer (CERN)

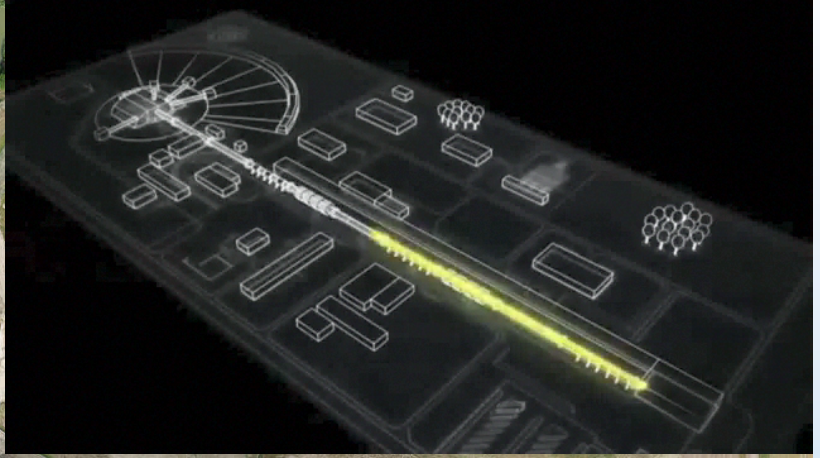
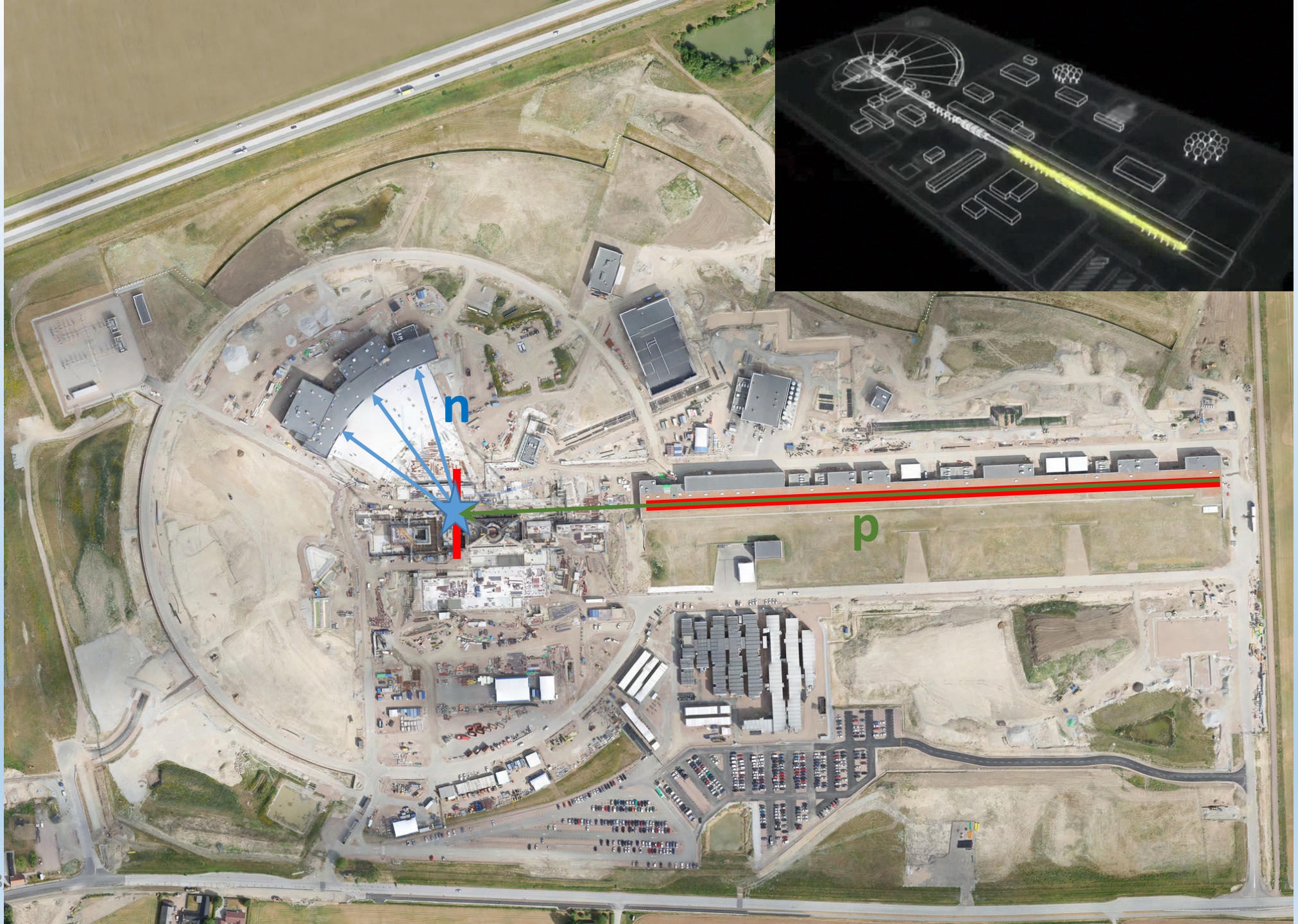
Shinji Machida, Chris Prior (RAL)

Ben Freemire, Jeffrey Eldred (Fermilab)

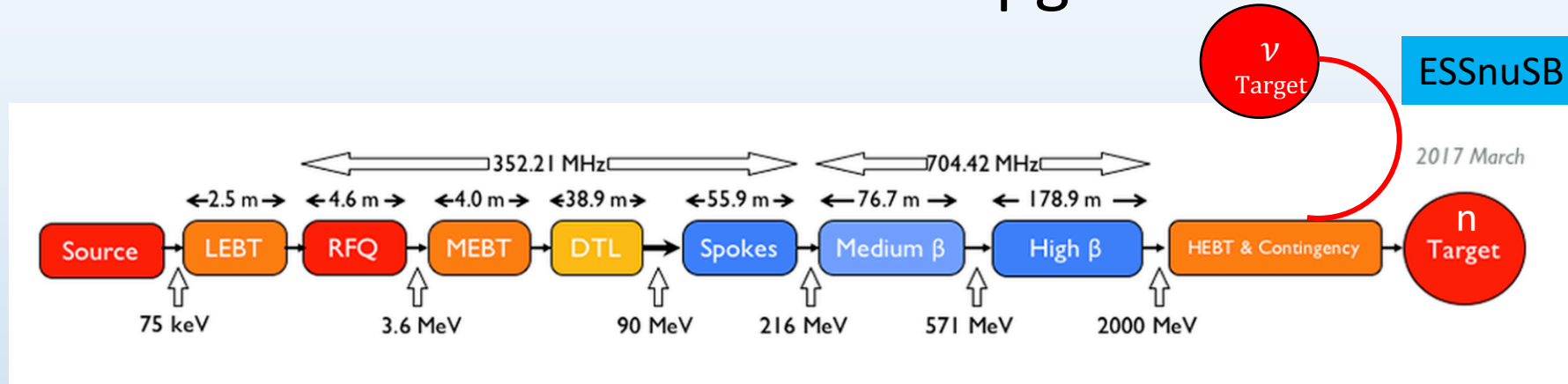
Maya Olvegård, Ye Zou (UU)

The European Spallation Source, ESS





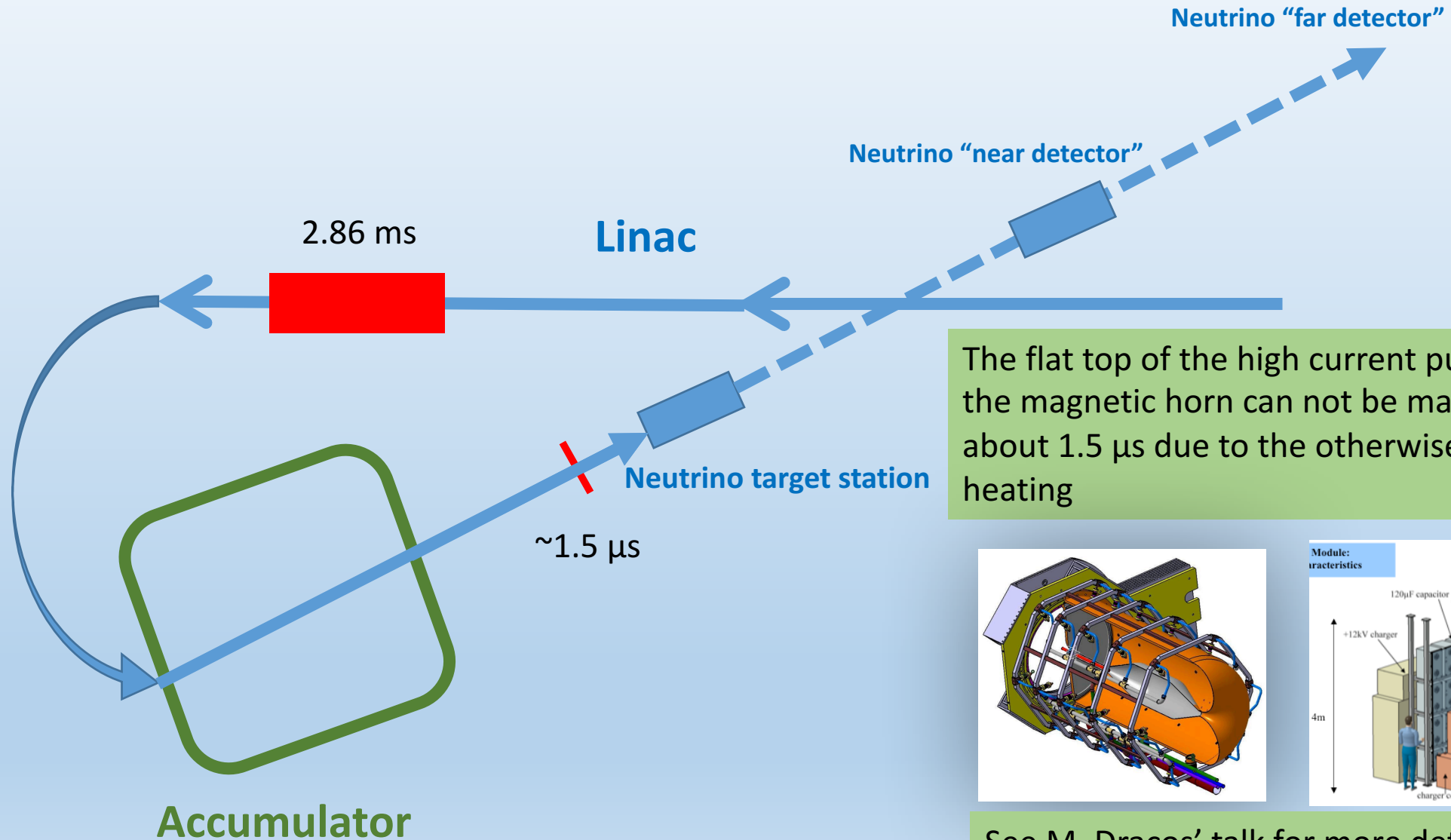
The ESS Linac for neutrons and upgrade for neutrinos



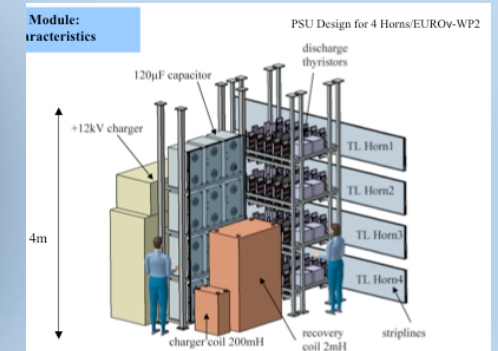
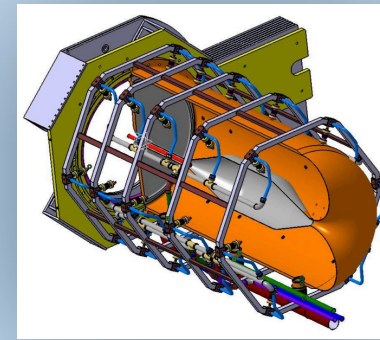
See Björn Gålnder's talk for more details

| 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

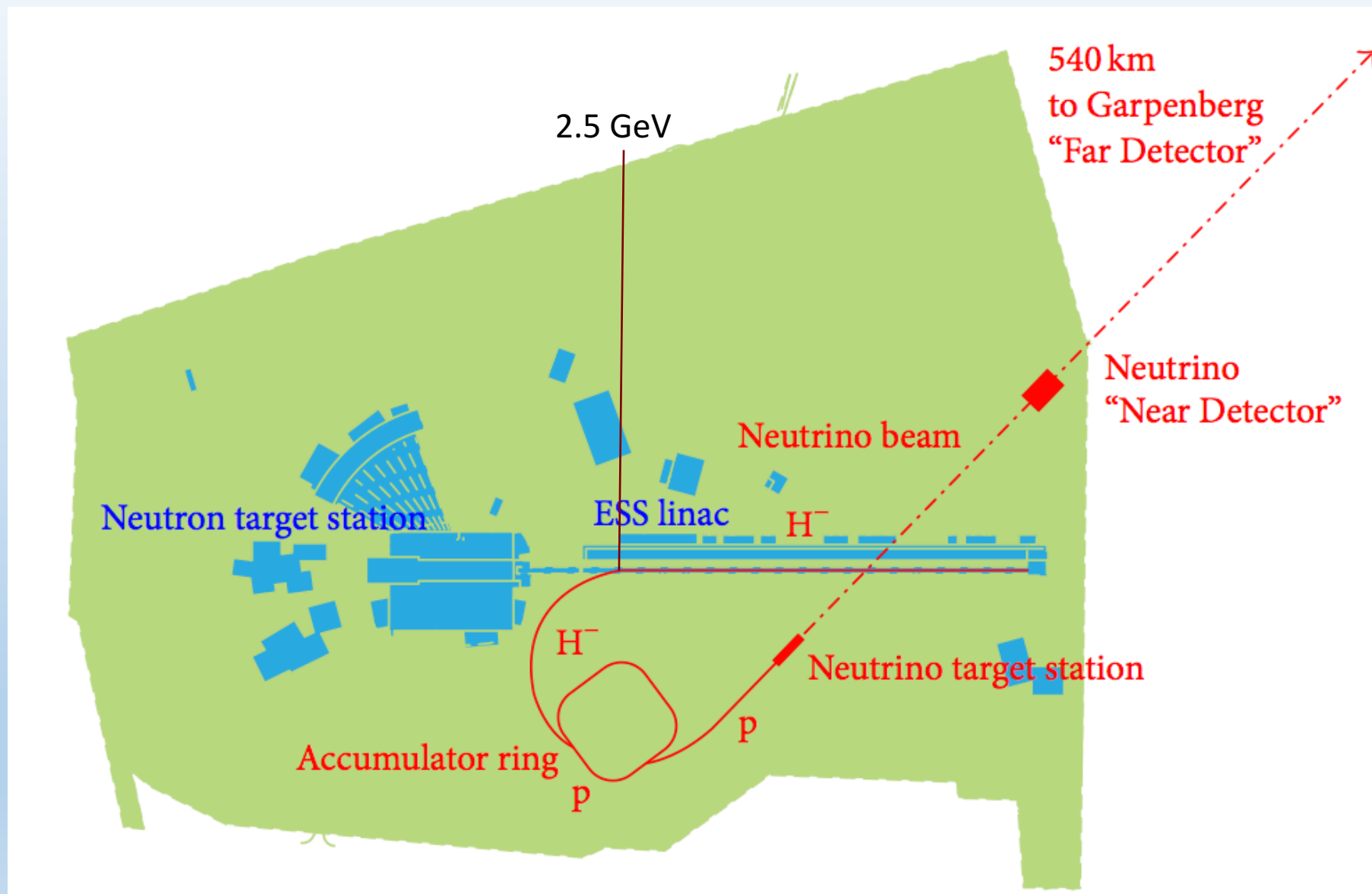


The flat top of the high current pulse of 350 kA in the magnetic horn can not be made longer than about $1.5 \mu\text{s}$ due to the otherwise excessive ohmic heating



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

$$\Delta Q_{x,y} = - \frac{1.1 \times 10^{15} \cdot r_0 N}{2\pi E_{x,y} \beta^2 \gamma^3 Bf}$$

1.1×10^{15} (circulating protons)
 r_0 (Classical radius)
 N (Beam intensity)
 $E_{x,y}$ (Transverse emittance)
 $\beta\gamma$ (Relativistic factors)
 Bf (Bunching factor)

75 π mm mrad (for $E_{x,y}$)
 27.58 (for $\beta^2 \gamma^3$)
 0.4 (for Bf)

- 1.1×10^{15} circulating protons in a ring with circumference corresponding to about 1.5 μ s 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

Multi-turn injection from linac to accumulator

Charge-exchange injection

Direct proton injection

Lorentz stripping

Foil-based stripping

Foil-free stripping

Low demanding
for Linac

Much beam loss on septum
with space-charge tune shift

May cause premature
stripping and limit
maximum magnetic
field

High stripping
efficiency

Stand high temperature
and large shock waves

good
lifetime

Laser stripping

Not fully stripped H^- or H^0
ions and stripped electron
and foil scattering

No issues caused
by the foil

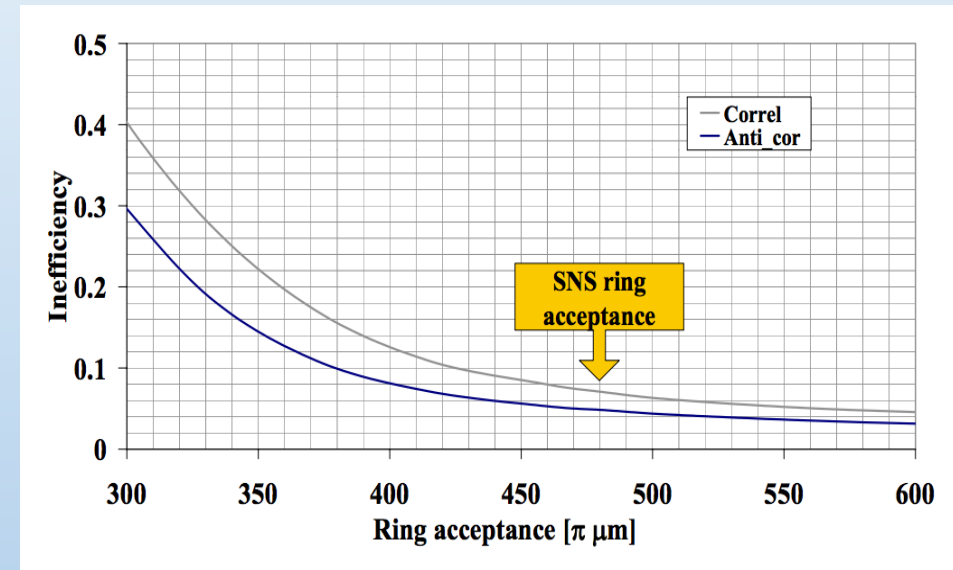
Pulse duration limited by
average laser power

Development on going
at the SNS

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

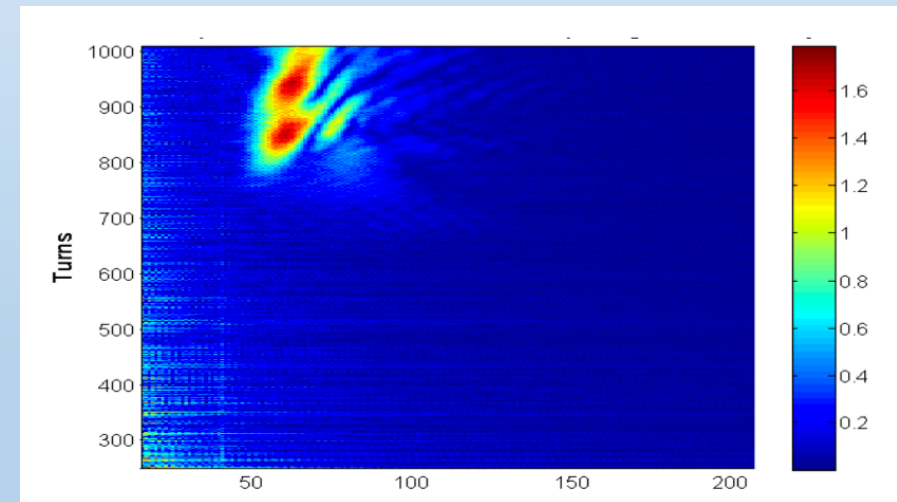
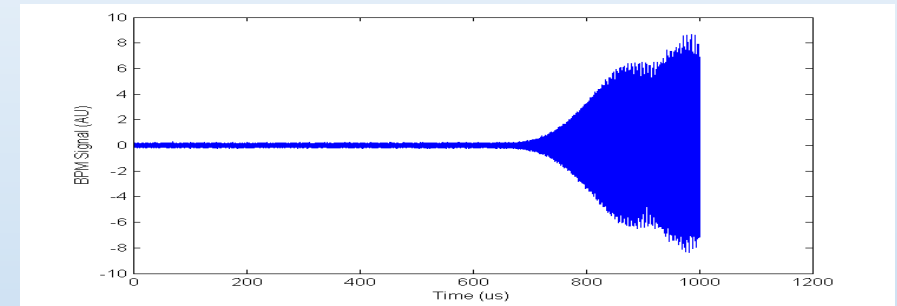
N. Catalan-Lasheras



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

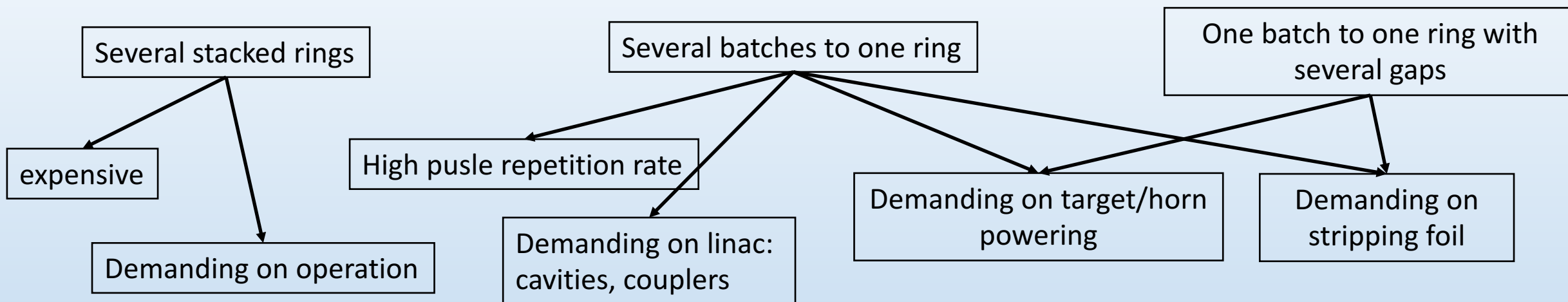
- H^- source to be added, accelerate proton and H^- pulse interleaved
- High average power: from 5 MW to 10 MW, a big step
- Linac equipment to be adapted

➤ From transport line

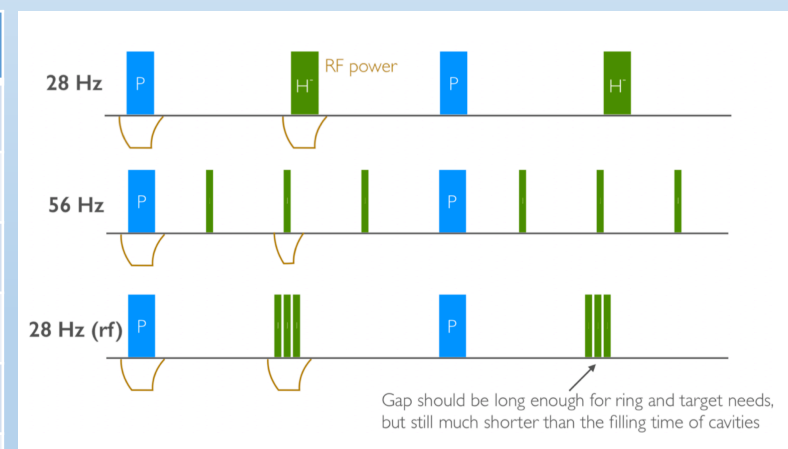
- Beam loss from Lorentz stripping (site layout has taken this into account)

Preliminary design of the ESSnuSB accumulator

Beam pulse structure schemes

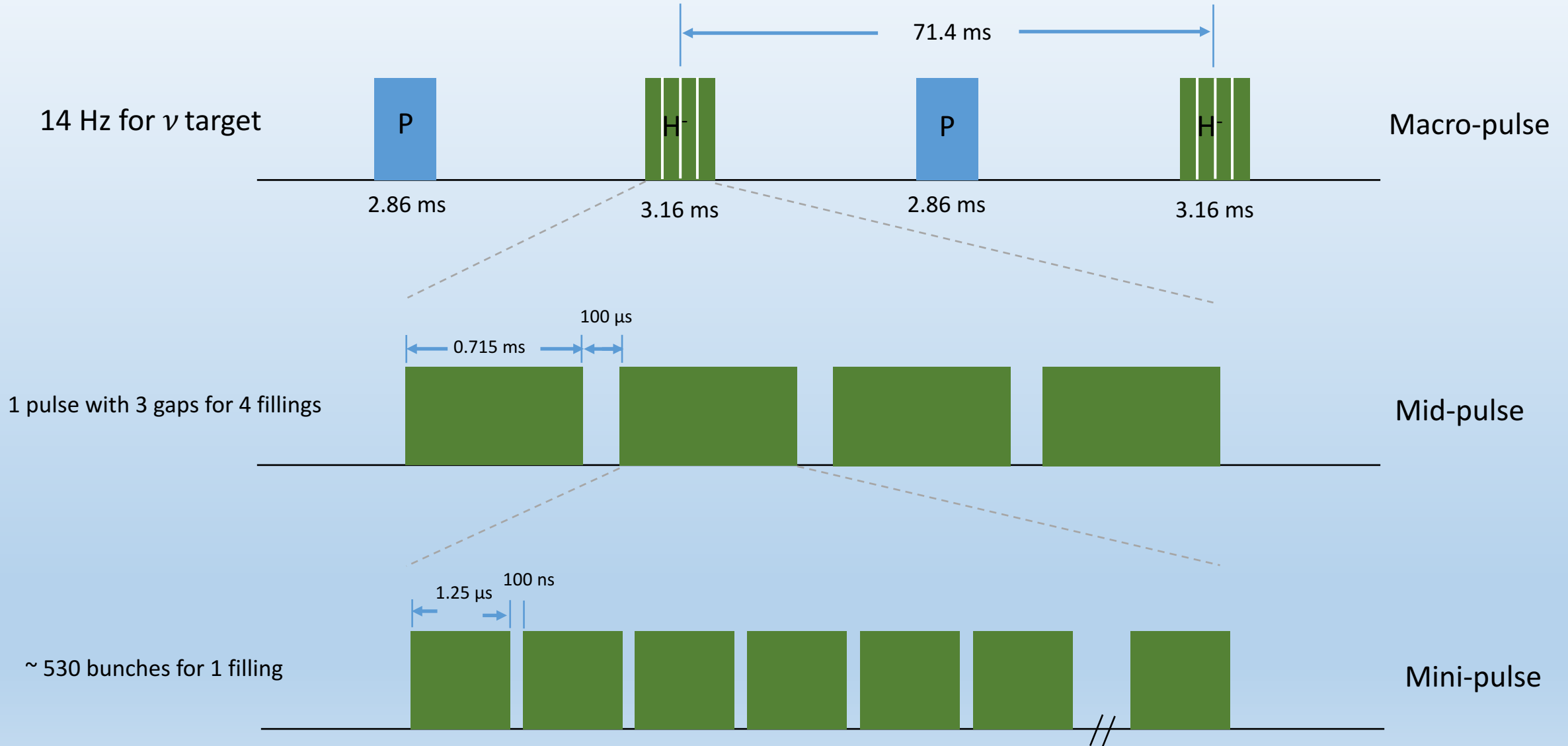


| | 1 Ring 1B L | 1 Ring 3B F | 3 Ring 1B F | 1 Ring 1B P | 3 Ring 3B P |
|--------------------------|-------------|-------------|-------------|-------------|-------------|
| Number of rings | 1 | 1 | 3 | 1 | 3 |
| Linac beam batches | 1 | 3 | 1 | 1 | 3 |
| Linac Pulsing [Hz] | 28 | 56 | 28 | 28 | 56 |
| 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 [μ s] | 100 | na | >100 | 100 | na |
| Inj. stripping | laser | foil | foil | na | na |



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

Baseline beam pulse structure



H⁻ foil-stripping injection

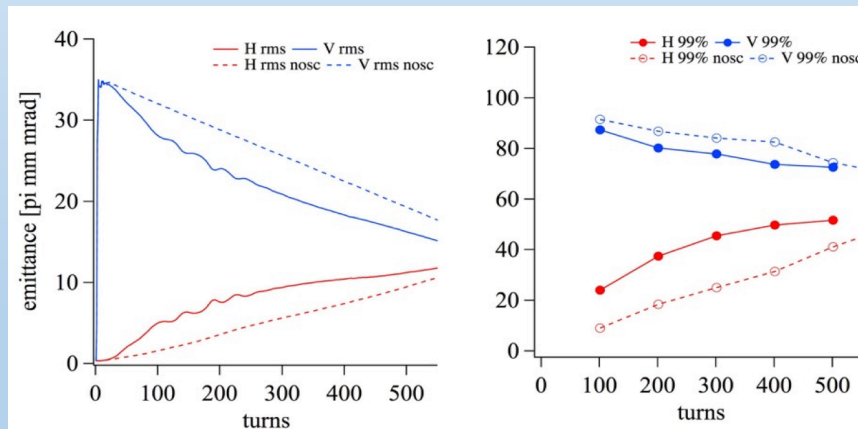
M. Olvegård

With J-PARC like lattice

S. Machida

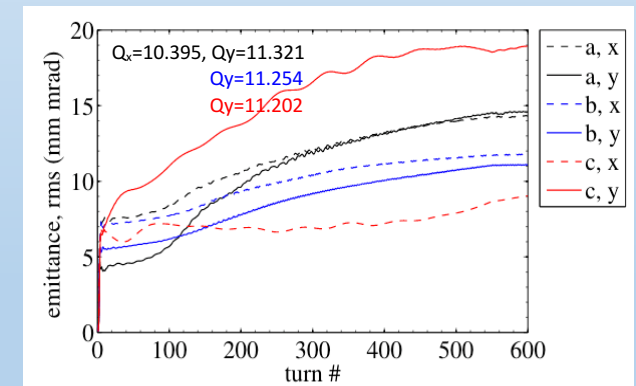
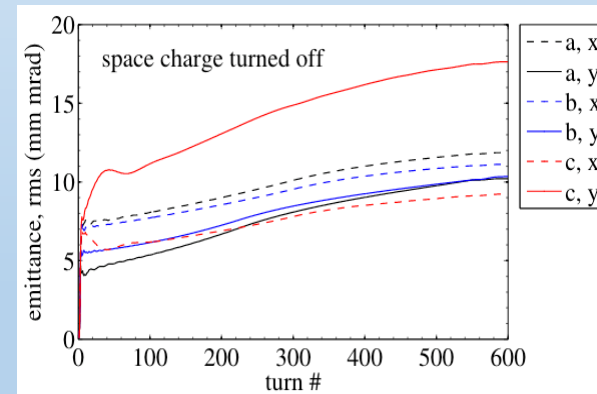
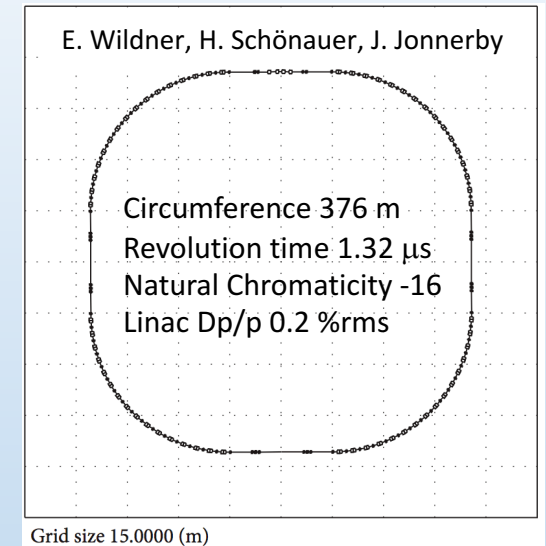
Anti-correlated painting

| | |
|---------------|-----------|
| 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



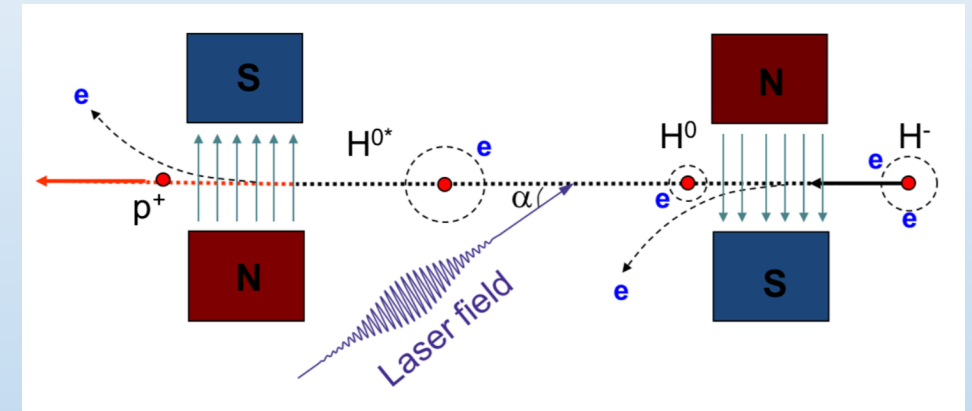
First simulations (multi-turn injection with correlated and anti-correlated painting) show **no worrying space charge** at 2 GeV

laser stripping

- So far, laser stripping is the most promising foil-free alternative stripping scheme
- Latest demonstration of laser stripping for **microsecond pulse (11 μ s)** 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

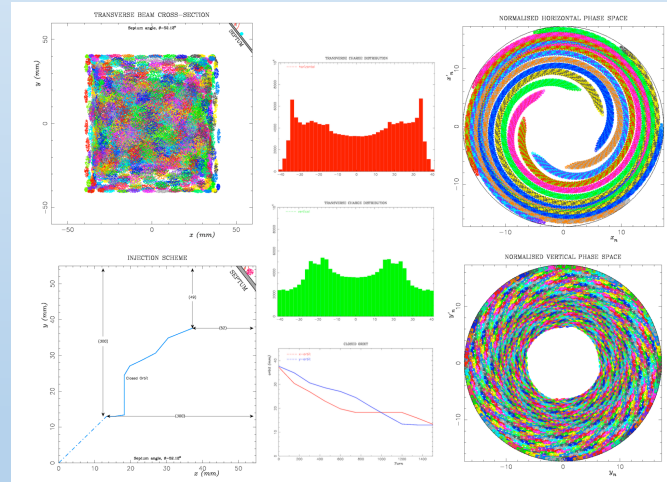
Courtesy Chris Prior

- 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 (μ s) | 1.32 |

Space charge effect considered

Space charge effect not 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 $\sim 17\%$
 - clear opportunities to improve scheme by modifying orbit bumps to allow for tune shift.
 - iterative optimising process.

**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 $\theta = 52.12^\circ$

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

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 | |

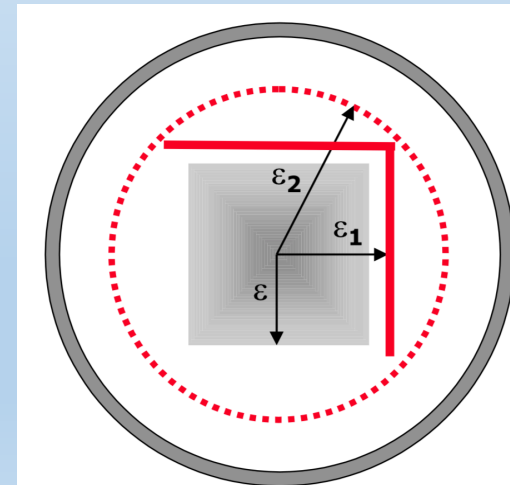
ε beam geometric emittance
 ε_1 primary collimator emittance
 ε_2 secondary collimator emittance

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

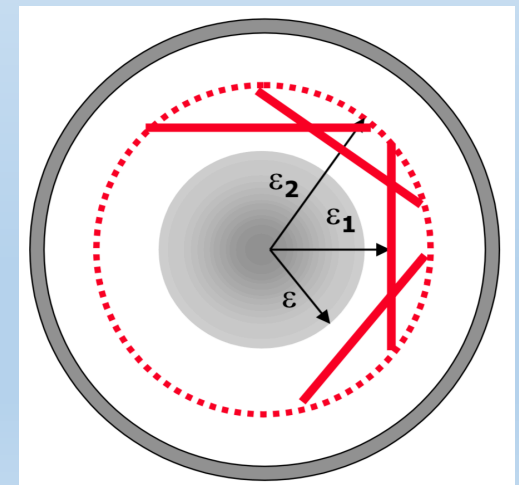
Anti-correlated painting $\varepsilon_2 > \varepsilon_1 > \varepsilon$

Unit: π mm mrad

16/08/18



Correlated painting

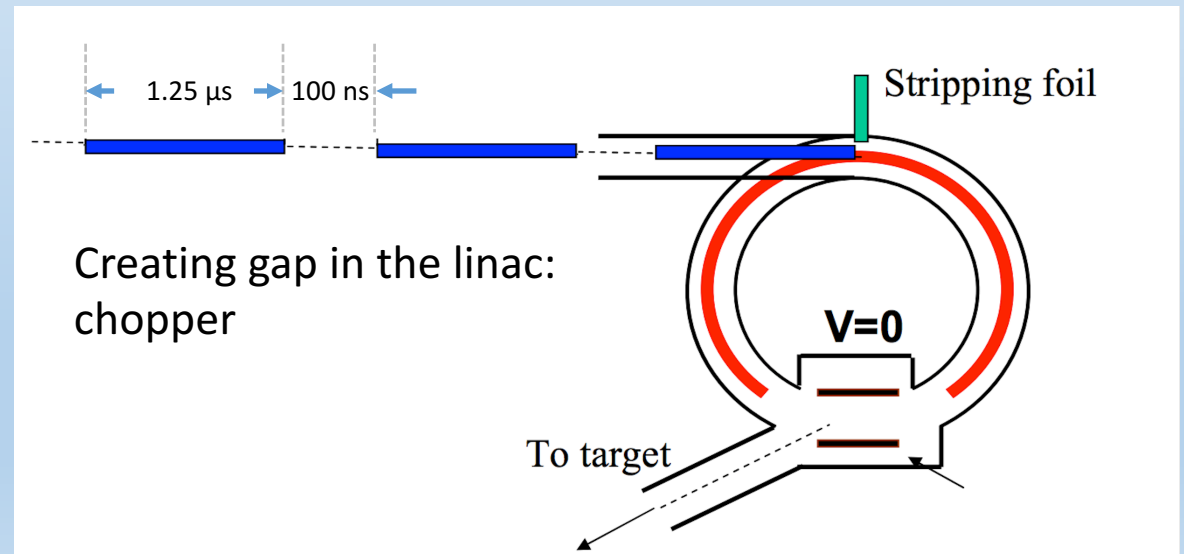


Anti-correlated painting

A. Aleksandrov

-
- A graph showing voltage (volts) on the y-axis versus time on the x-axis. The y-axis has a mark for V_{max} . The x-axis has a mark for 100~200 ns. The graph is divided into two regions: 'accumulation' (low voltage) and 'extraction' (high voltage). A magenta curve shows the voltage rising from the accumulation level to the extraction level. A black dot is placed on the rising part of the curve, with an arrow pointing to it from the text '? Beam lost'. Another arrow points to the rising part of the curve with the text 'Deflector rise-time'.

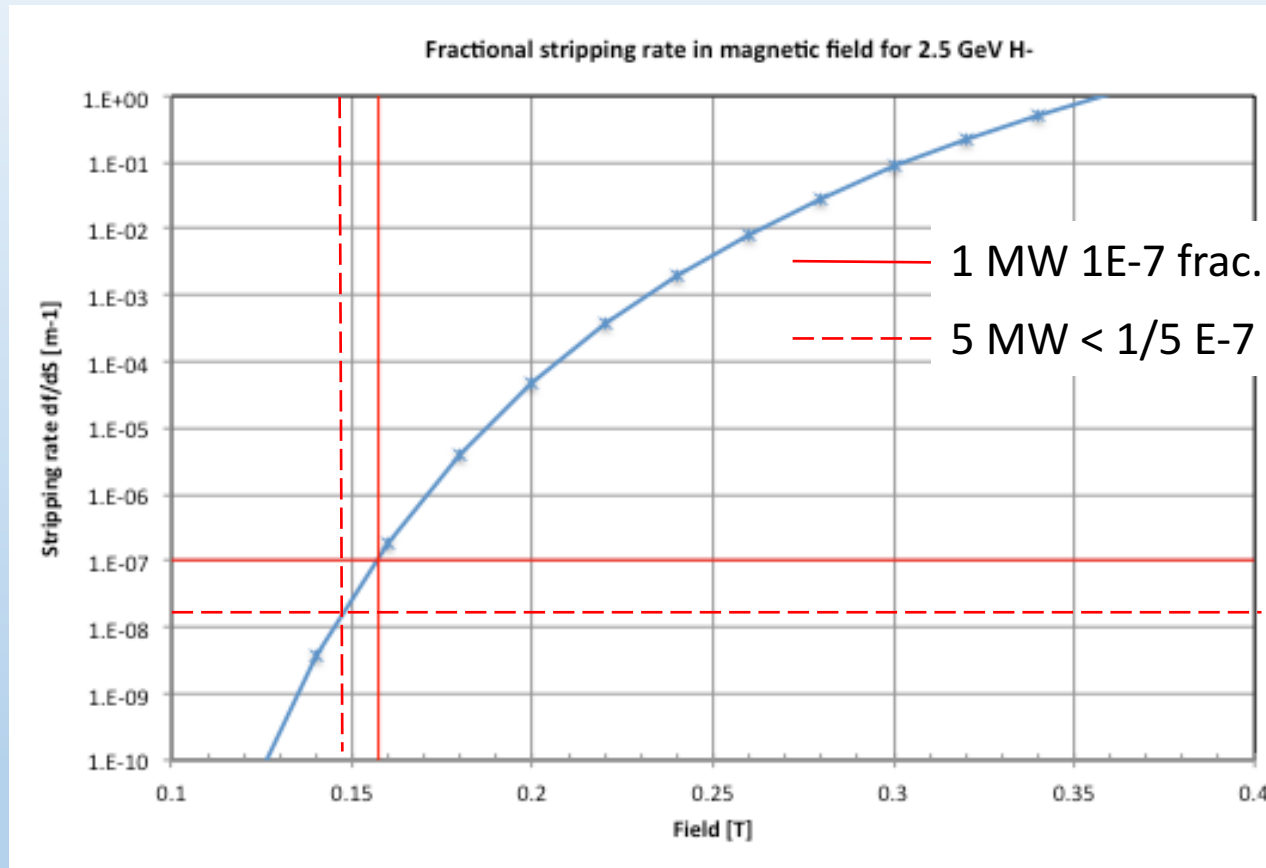
S. Machida



H⁻ Transfer Line: stripping rates

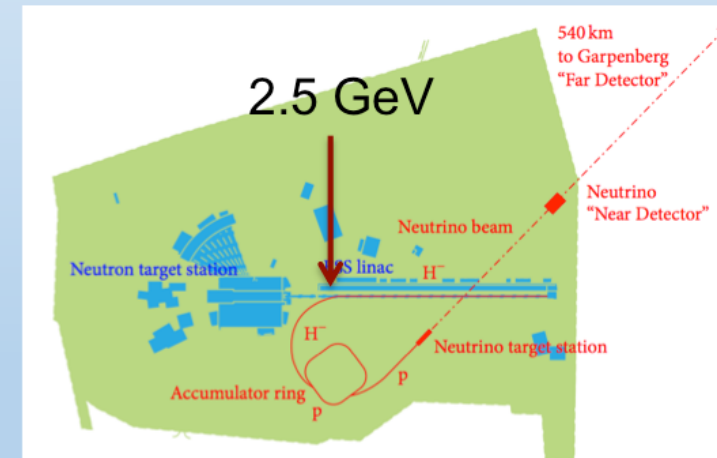
E. Wildner

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



1 MW 1E-7 frac. loss to get < 0.1 W/m

5 MW < 1/5 E-7 frac. loss -> ~ 0.15 T

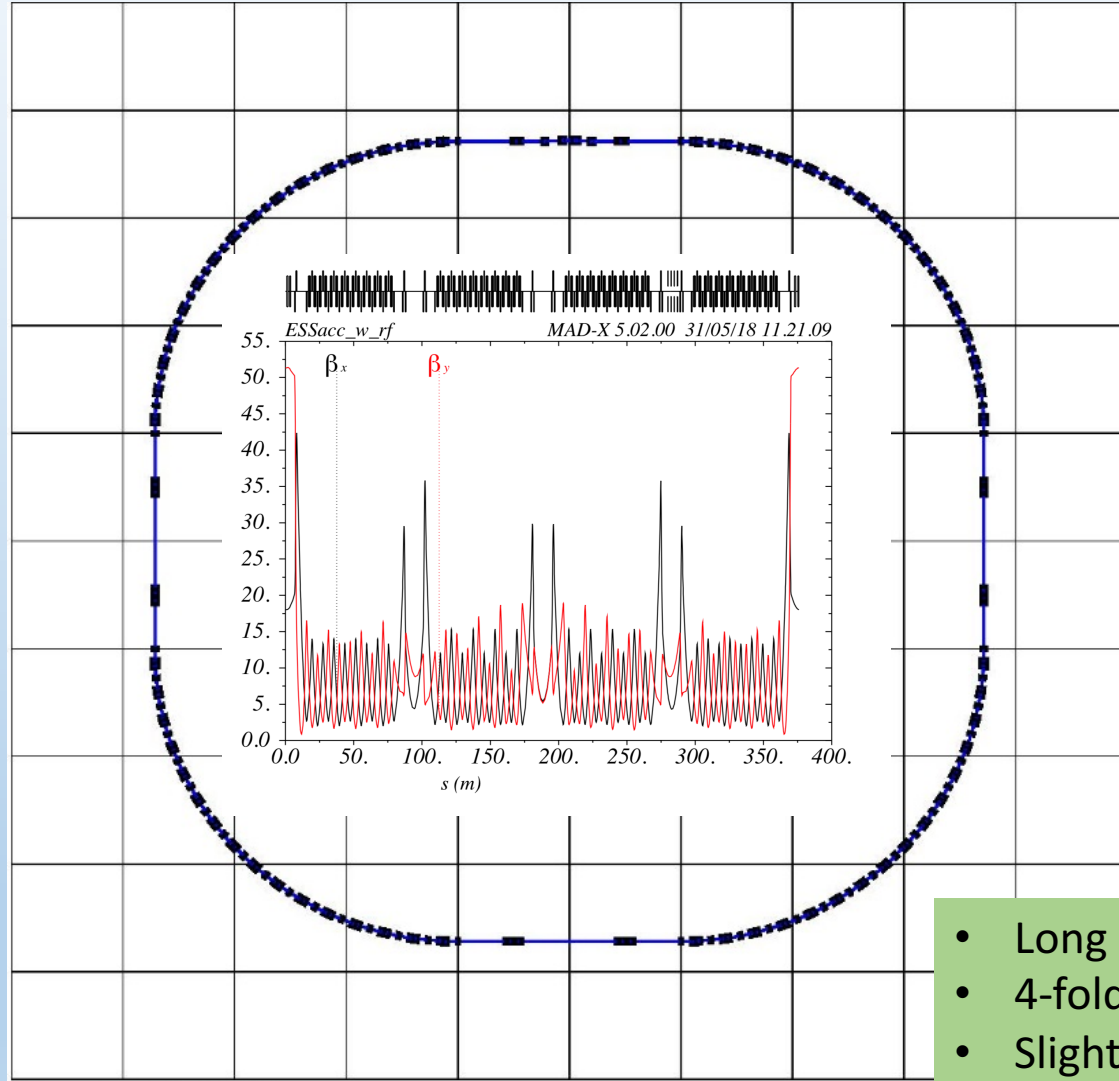


0.15 T and 2.5 GeV: $B\rho=11.02$ Tm, $\rho=73.5$ m in dipoles
66% dipole filling factor, transfer line tunnel $\rho=111$ m

Preliminary results with the current lattice

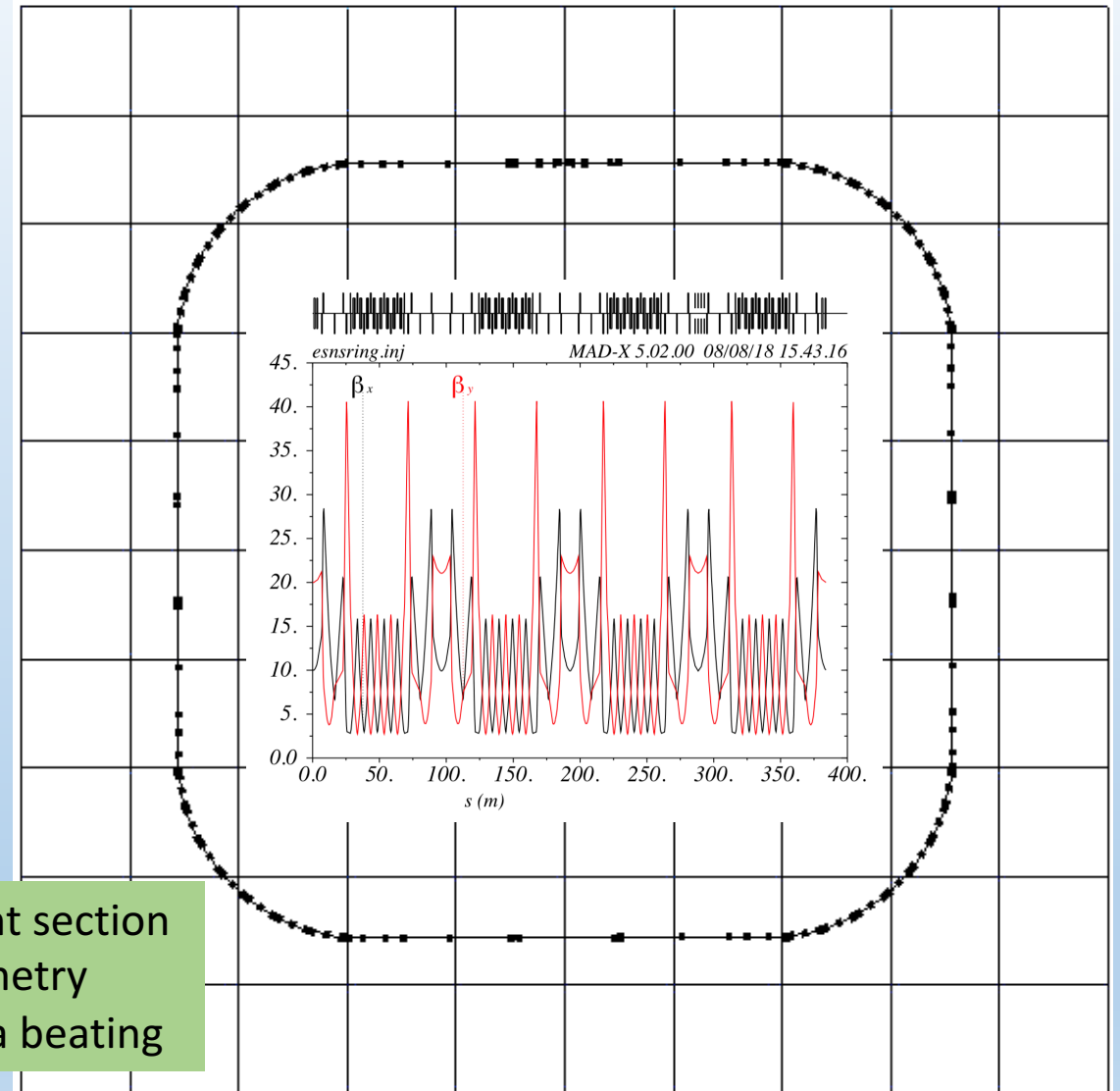
The lattice development

Horst Schönauer



Grid size 15.0000 [m]

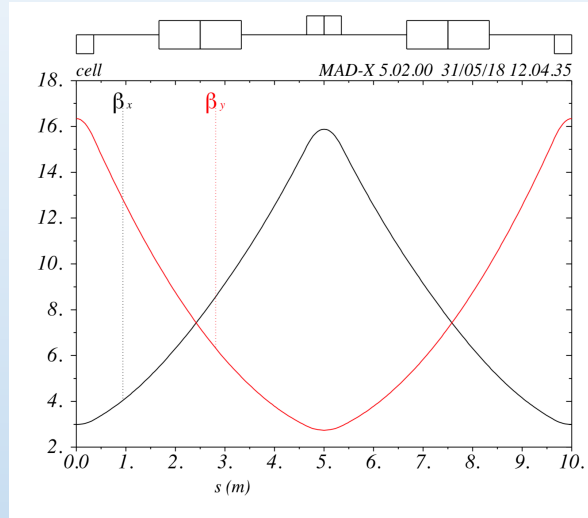
- Long straight section
- 4-fold symmetry
- Slightly beta beating



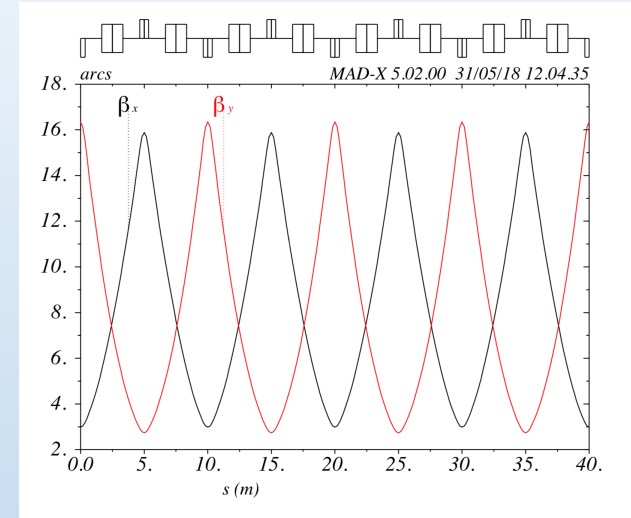
The lattice development

- 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

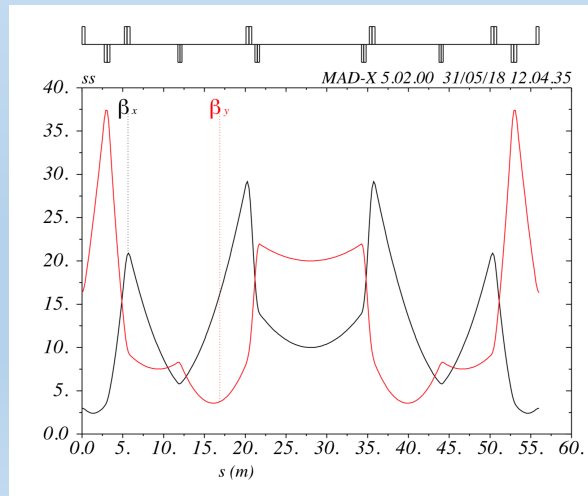
Cell



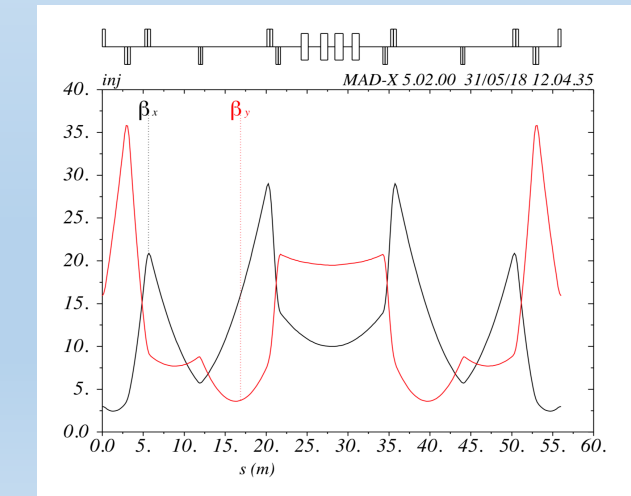
ARC



Straight



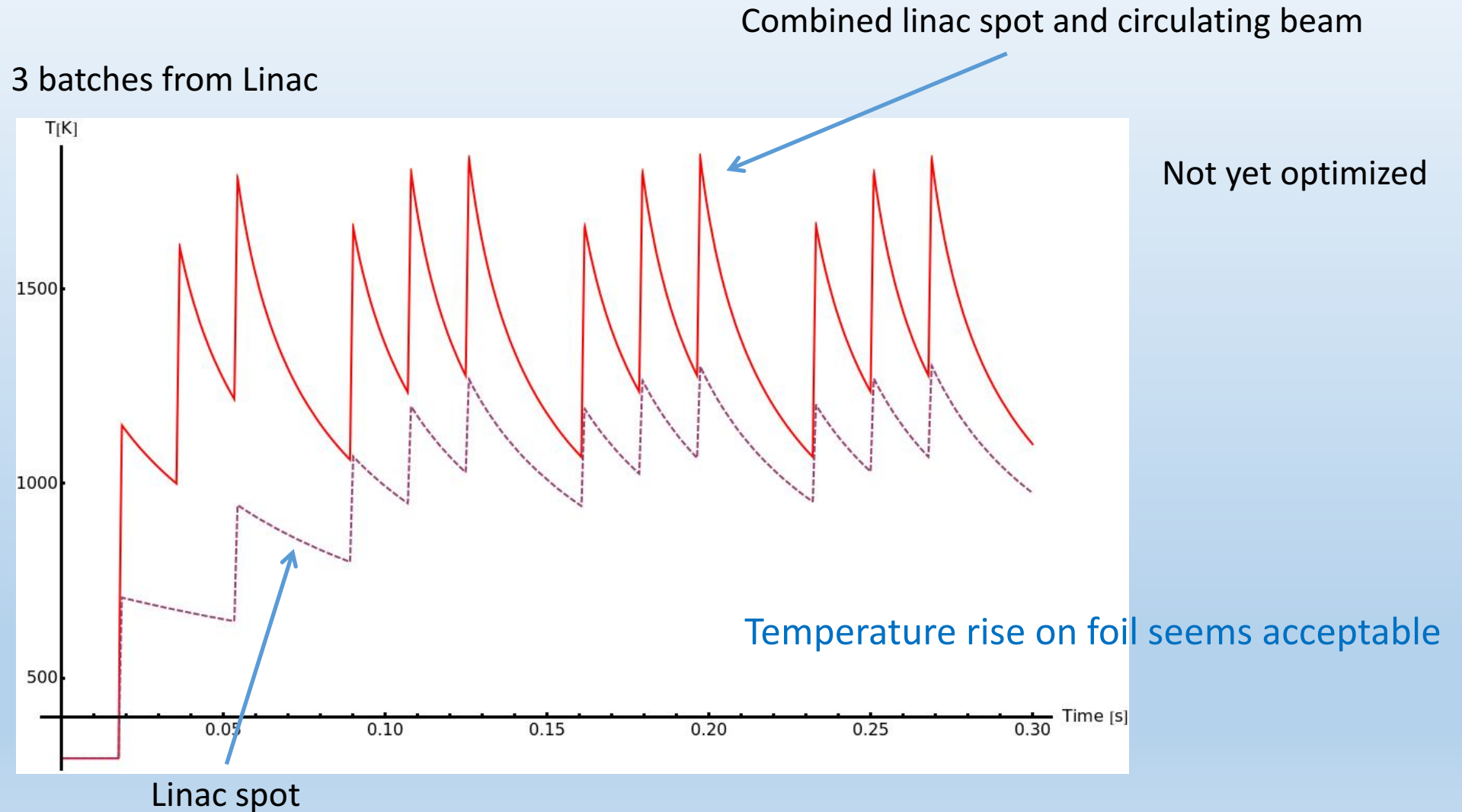
Injection



| 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

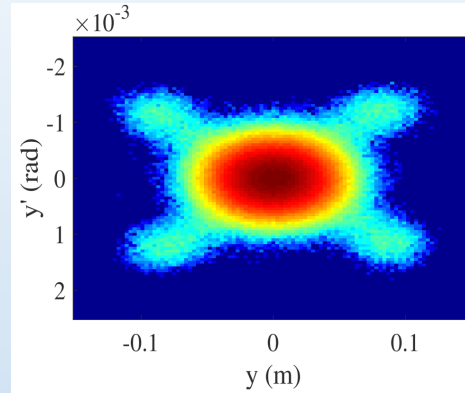
Horst Schönauer



SIMPSONS tracking without space charge

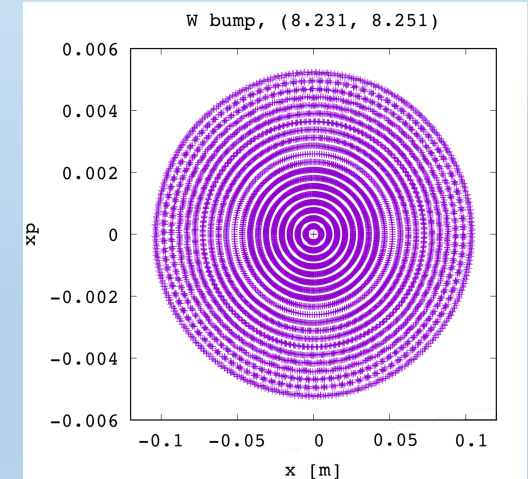
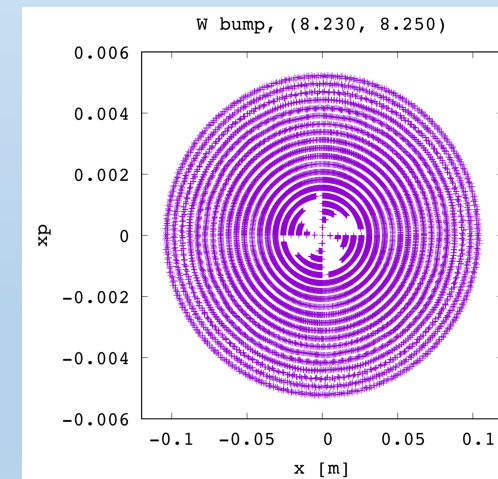
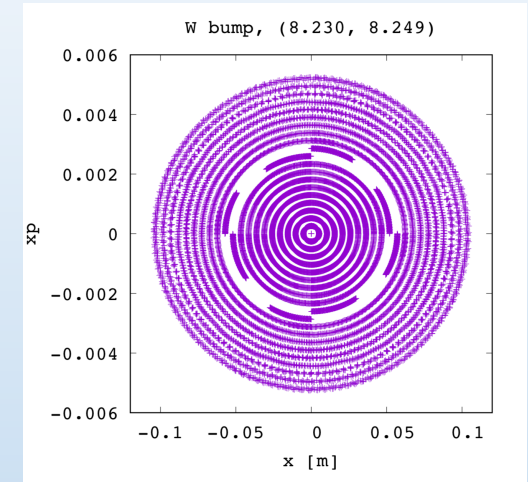
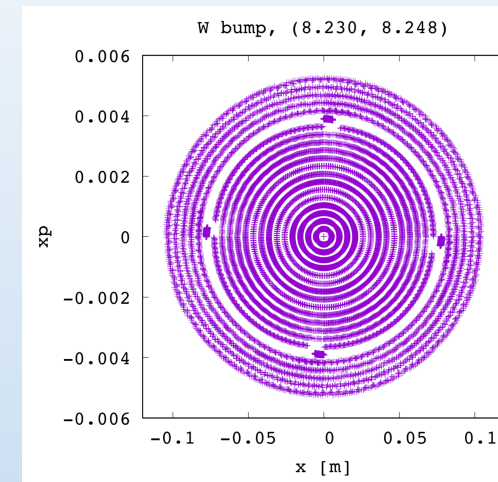
Shinji Machida

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



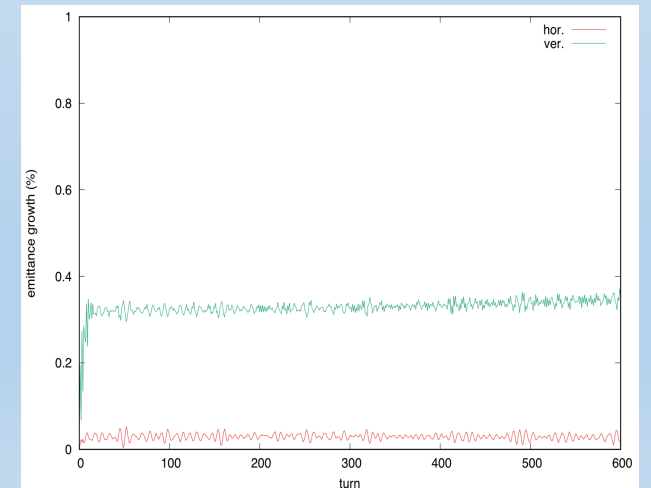
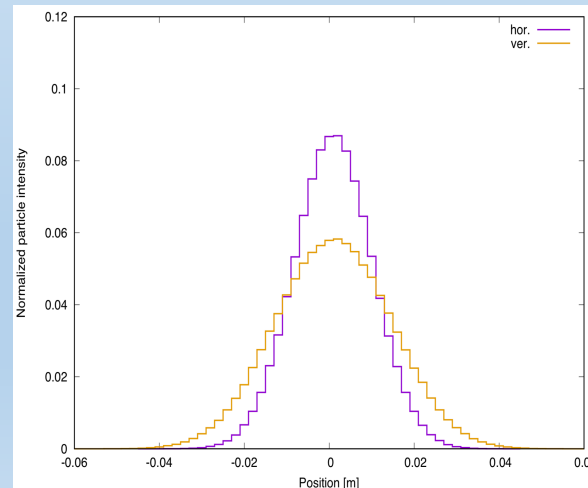
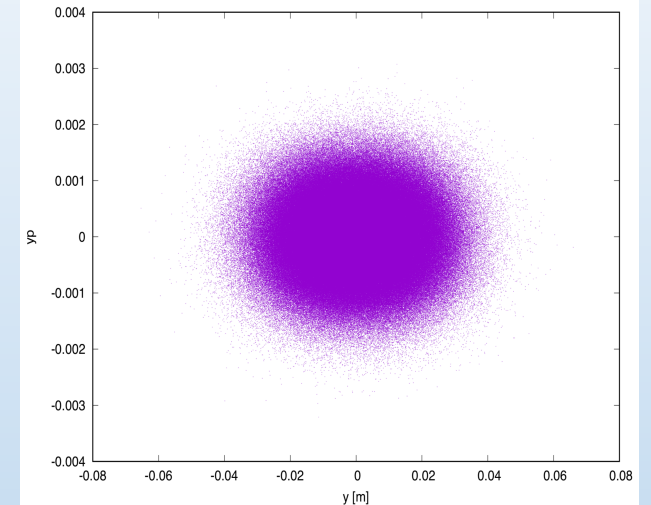
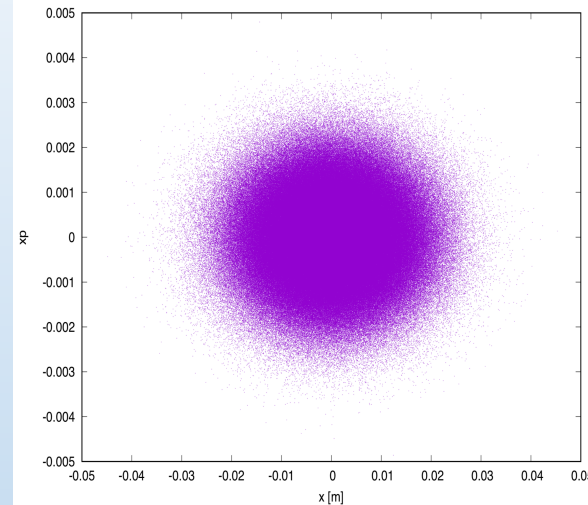
M. Olvegård

- Results show a Poincare map of 1000 turns
- No space charge is included
- Tune is adjusted by only q_f and q_d 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



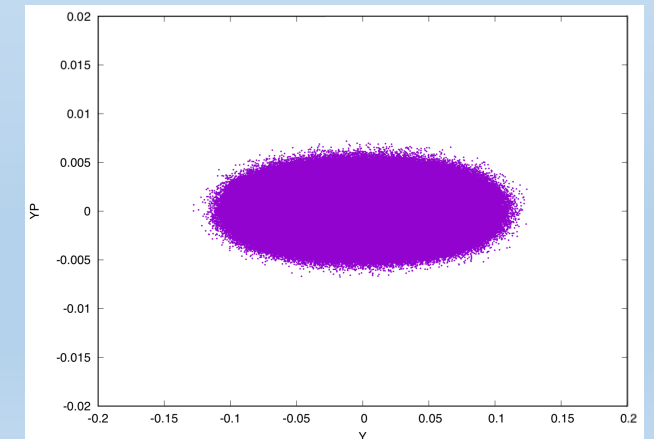
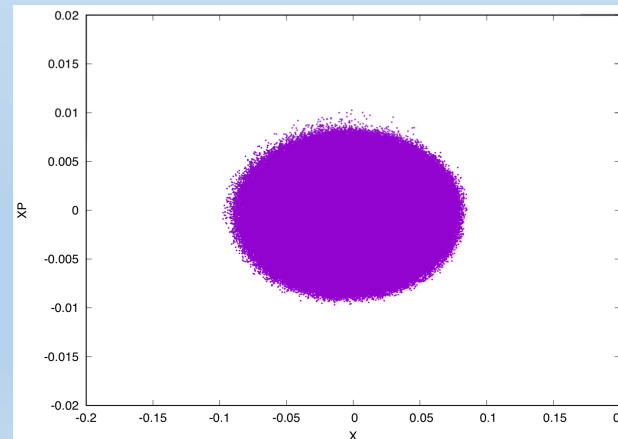
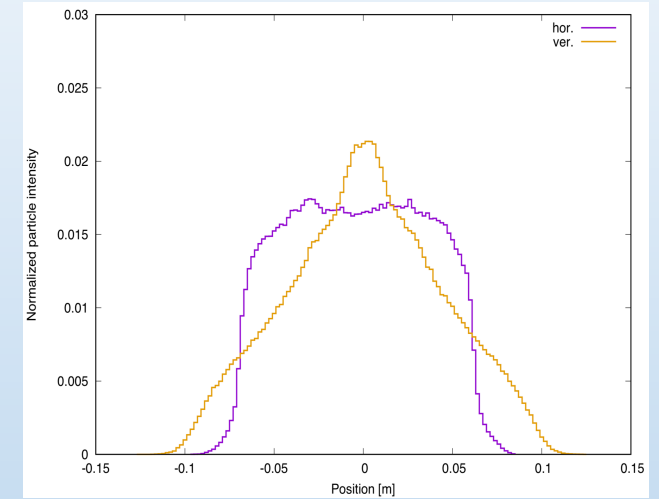
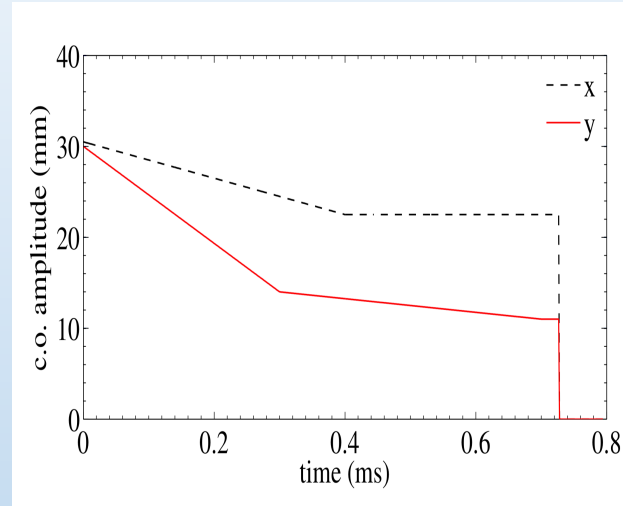
Multi-particle simulation: full injection

- Full intensity injection to see emittance evolution
- Current lattice ($\nu_x = 8.27, \nu_y = 8.34$)
- 10^6 particles with 1σ 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: $0.25 \pi \text{ mm mrad}$
- Correlated painting
- Longitudinal distribution: uniform in z and 1D Gaussian 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

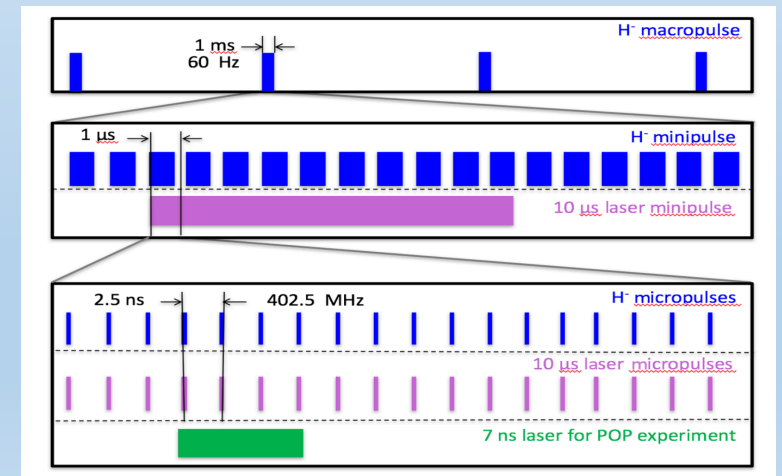
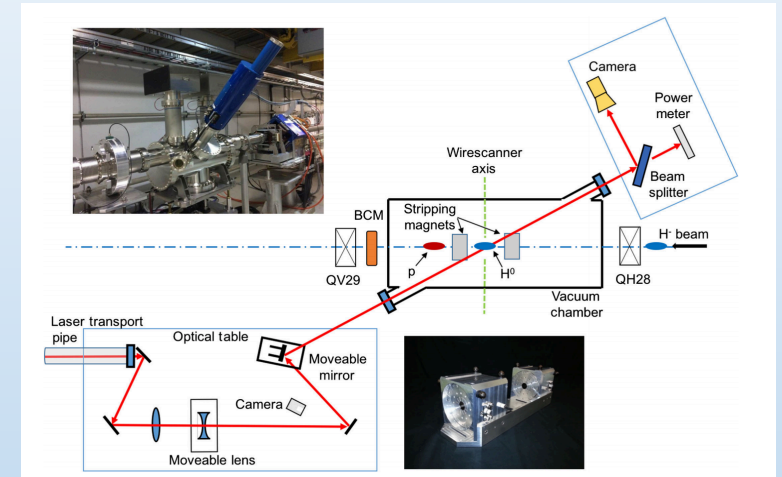
- ✓ Linac upgrades for the ESSnuSB possible to implement
- ✓ First design has been performed
 - ✓ 1 ring, based on SNS experience, 3 batches, 56Hz, foil stripping
- ✓ New baseline
 - ✓ 1 ring, 1 batch, 100 μ s gap, laser stripping, requiring lattice modification
- ✓ Optics: new design lattice, 4 fold, 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 mmrad is assumed first.

| <u>beam size</u> | <u>fraction</u> | <u>Emittance (un-nor.)</u> | <u>Emittance (nor.)</u> |
|------------------------|-----------------|----------------------------|-------------------------|
| 3 sigma | 98.9% | 75 mm <u>mmrad</u> | 225 mm <u>mmrad</u> |
| 2 sigma | 86.5% | 33 mm <u>mmrad</u> | 100 mm <u>mmrad</u> |
| 1 sigma (<u>rms</u>) | 39.3% | 8.3 mm <u>mmrad</u> | 25 mm <u>mmrad</u> |

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

| <u>beam size</u> | <u>fraction</u> | <u>Emittance (un-nor.)</u> | <u>Emittance (nor.)</u> |
|------------------------|-----------------|----------------------------|-------------------------|
| 2 sigma | 100% | 75 mm <u>mmrad</u> | 225 mm <u>mmrad</u> |
| 1 sigma (<u>rms</u>) | 25% | 19 mm <u>mmrad</u> | 56 mm <u>mmrad</u> |