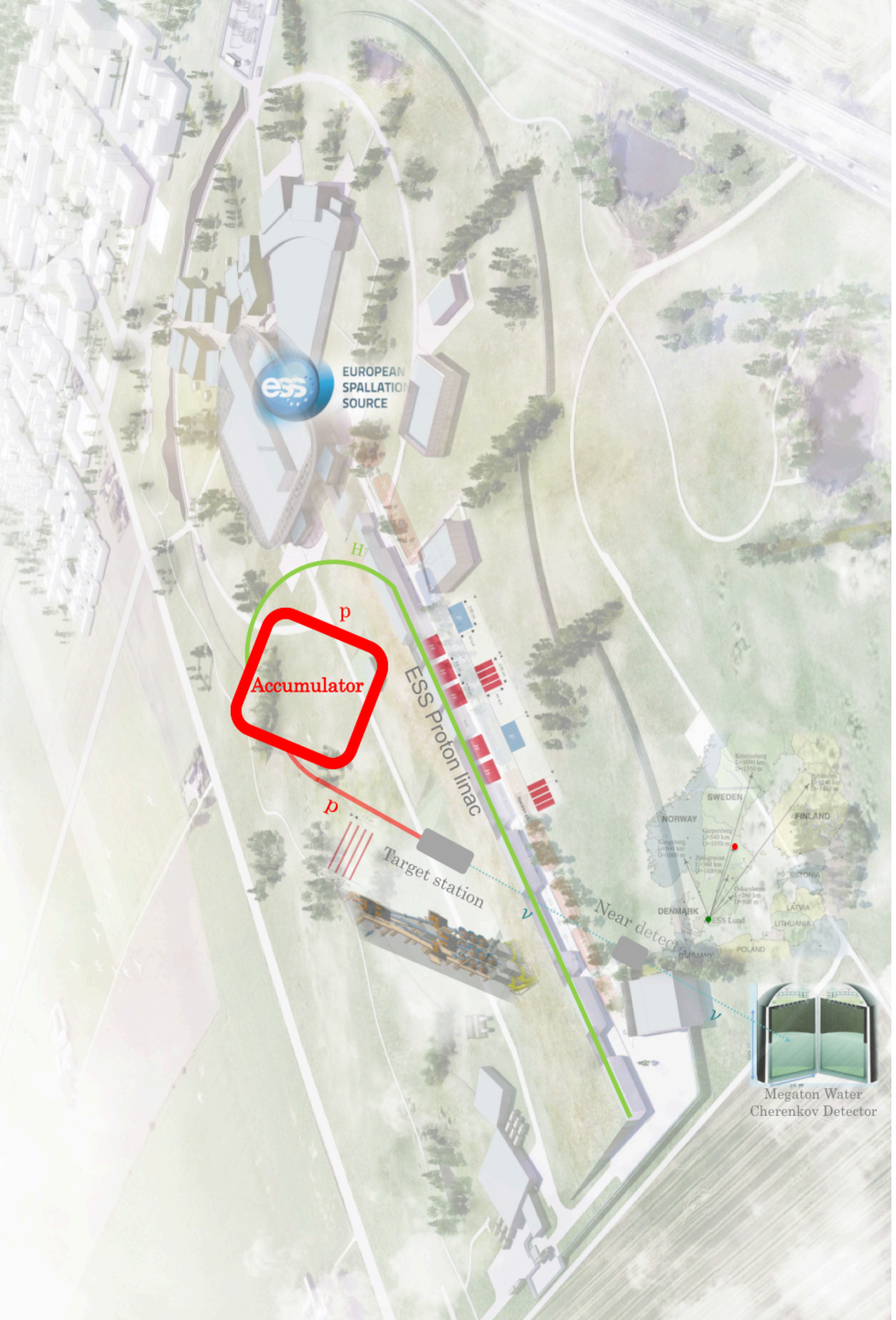


UPPSALA UNIVERSITET

Funded by the Horizon 2020 Framework Programme of the European Union

Progress of the ESSnuSB accumulator design

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

ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

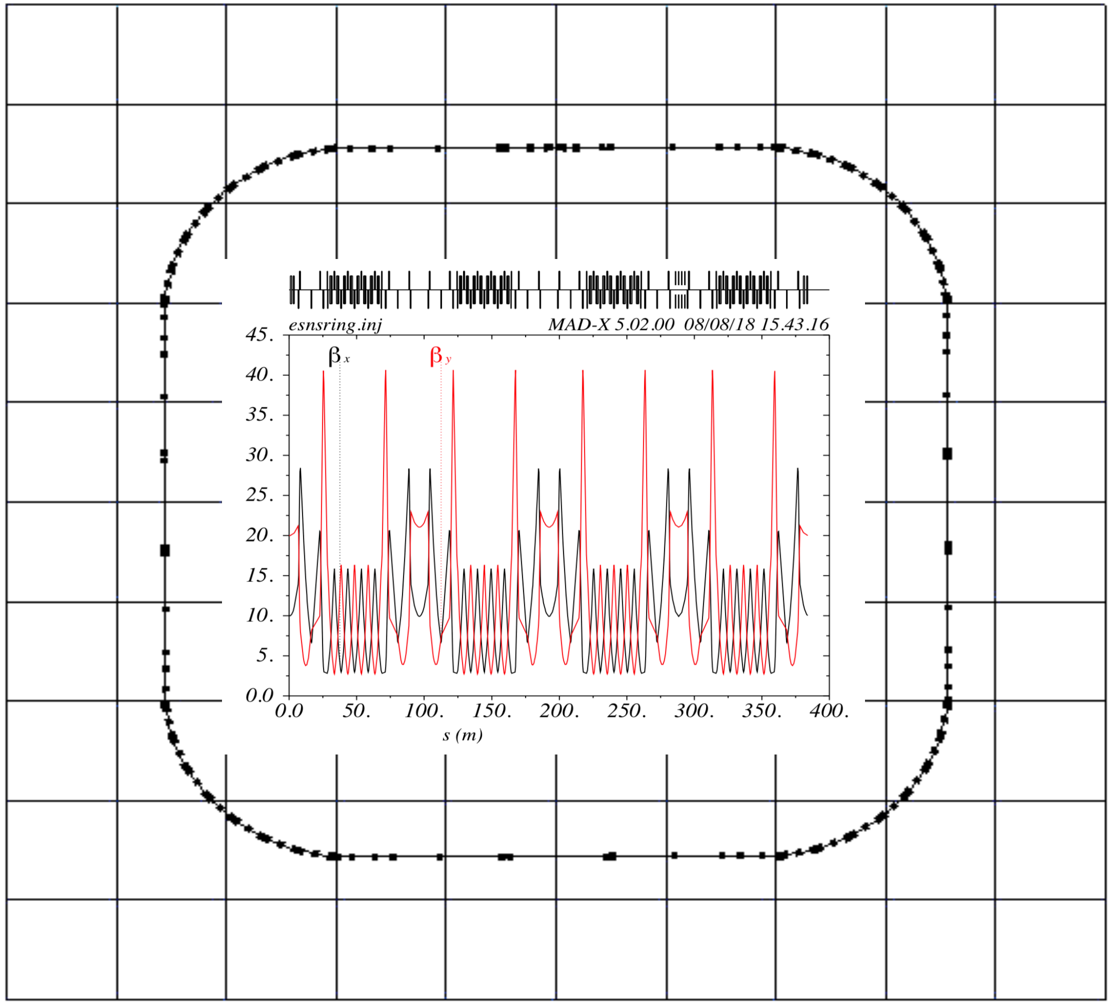
EuroNuNet

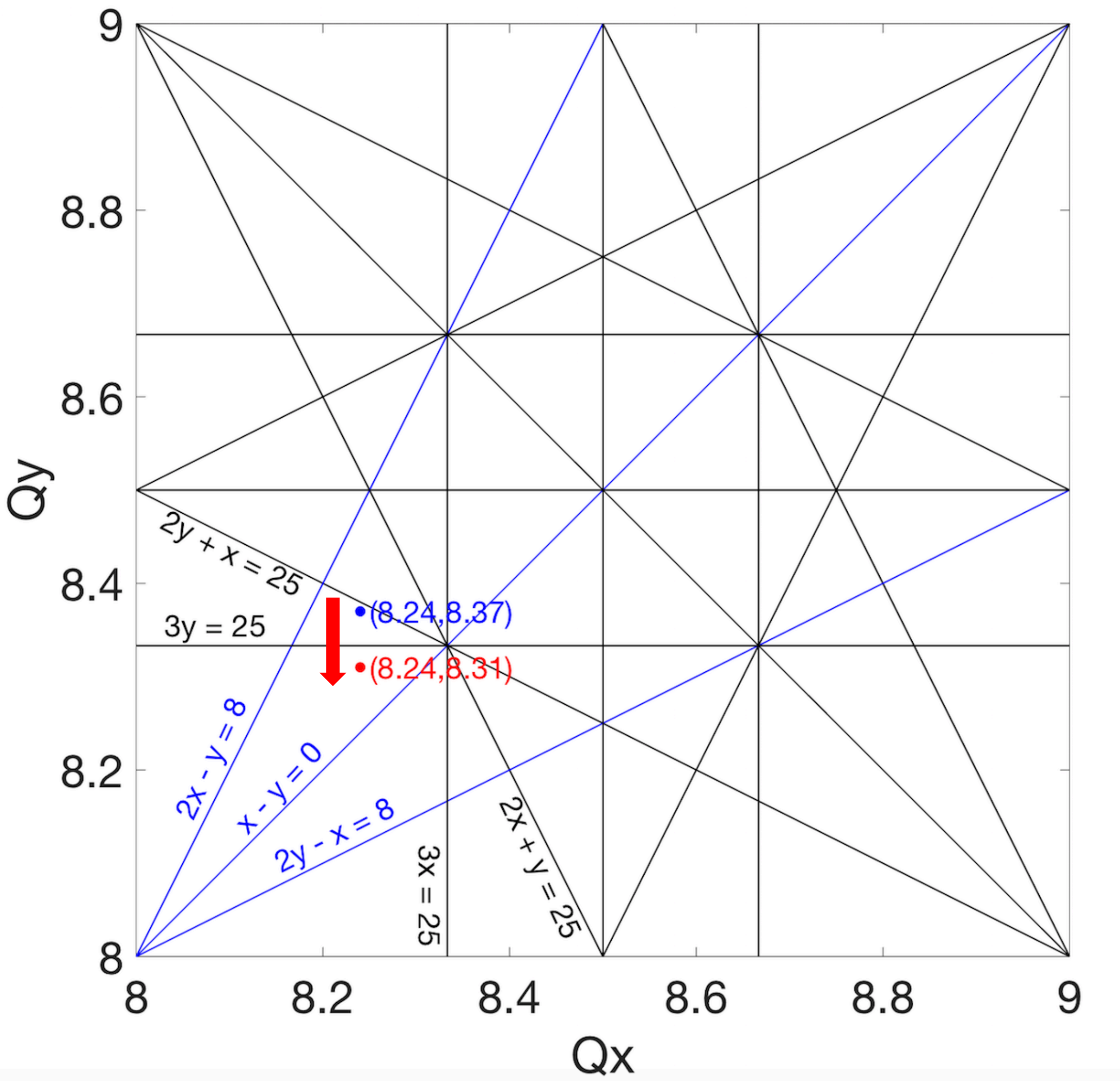
Main parameters

Parameters	ESSnuSB 28 Hz old	ESSnuSB 28 Hz new	ESSnuSB (70 Hz, 50 mA)	SNS (1.4 MW)
Beam power on target (MW)	4.03	5	5	1.4
Beam energy (GeV)	2	2.5	2.5	1.0
Beam intensity (ppp)	2.75×10^{14}	2.23×10^{14}	2.23×10^{14}	1.5×10^{14}
Average macro-pulse beam current (mA)	62.5	62	50	25
Pulse repetition rate (Hz)	28	28	70	60
Macro-pulse length (ms)	0.64	0.64	0.79	1
Pulse length after accumulation (μs)	1.22	1.2	1.2	0.7
Accumulation turns	474	481	597	1070
Bunching factor	~0.4	~0.9	~0.9	0.25
Un-norm. painted beam emittance πmm-mr	100	60	60	300
Space charge tune shift	-0.05 to -0.1	-0.022 to -0.044	-0.022 to -0.044	-0.15

Lattice and tune

Developed by Horst Schonauer



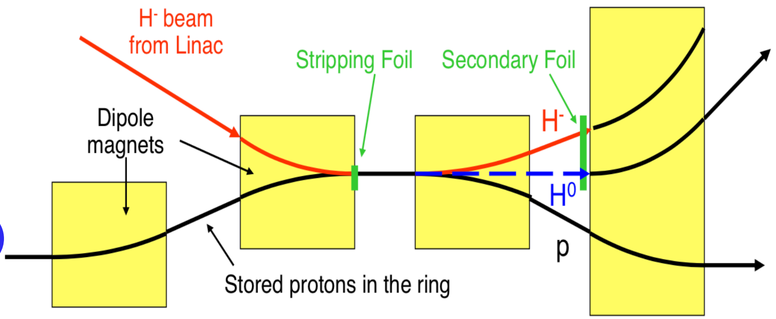


H^- injection

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

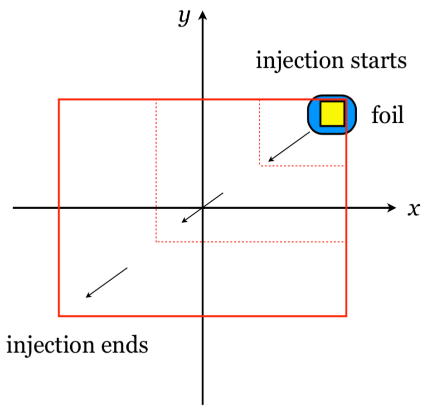
H^- beam passes through a thin foil, 2 electrons stripped by the foil to make H^- become proton

- Carbon foil is chosen for its non-hazardous, low-Z, withstand high temperatures, so on.
- Stripping efficiency
- Foil temperature
- Foil scattering (~10^{-5})
- H^0* beam loss
- Stripped electrons (~5.4 kW)

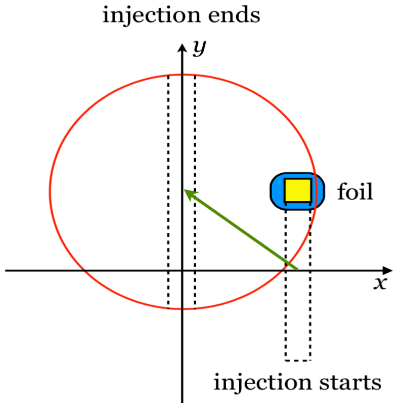


Transverse injection painting

- 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



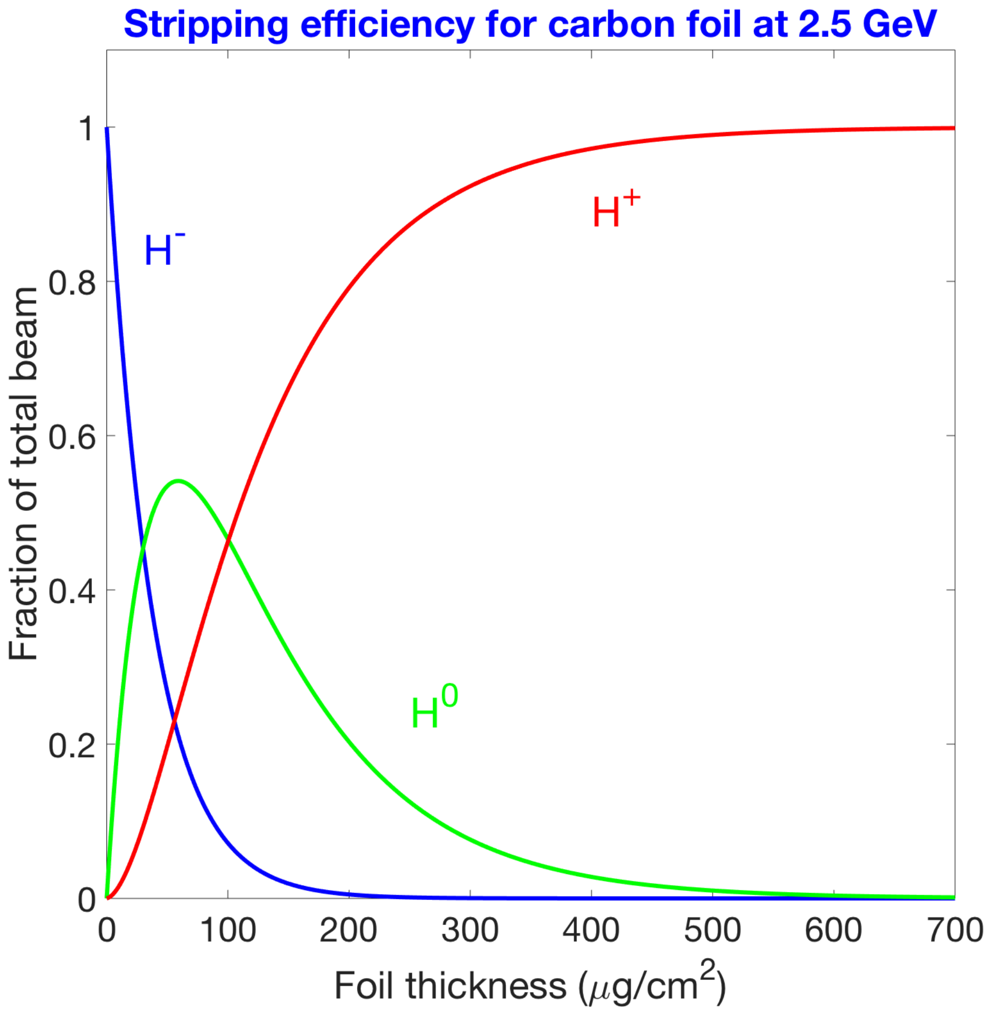
Correlated painting



Anti-correlated painting

Foil stripping efficiency

- Stripping efficiency is a function of foil material, foil thickness, foil density, beam species, and beam energy
- As the stripping foil thickness increases:
  - The fraction of the beam that is fully stripped increases (good)
  - The scattering of the injected and circulating beam also increases (bad)
  - The energy deposited in the foil increases, which can overheat and damage the foil (bad)
- Specifying the optimum foil thickness is a balancing act between the stripping efficiency, the scattering, and foil heating
- If stripping efficiency > 99%, thickness >500 μg/cm^2 , f(H^0) < 1%, f(H^-) < 2× 10^{-6}
- As an comparison: SNS ~ 300 μg/cm^2 ,injection energy 1 GeV;



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](#)

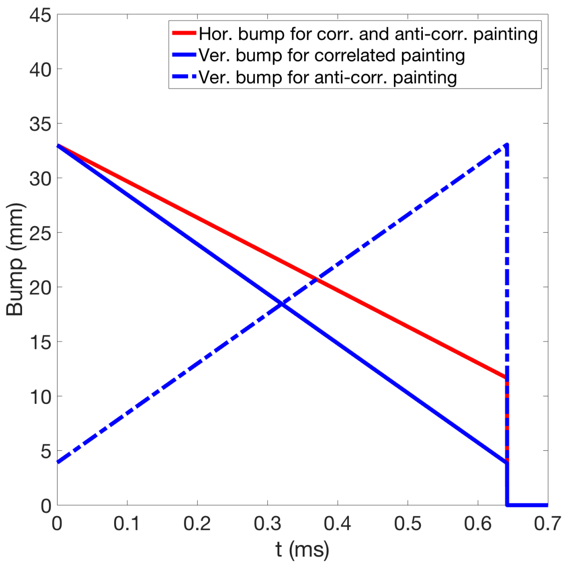
Configurations for simulation

- 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

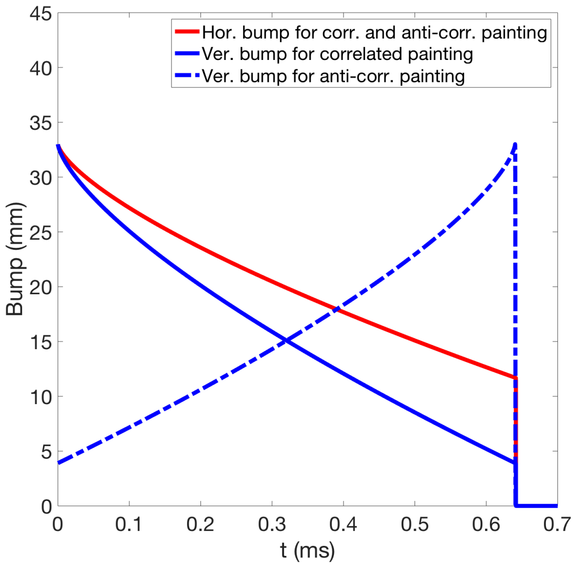
Basic parameters for simulations	**Value**
Hor./Ver. Norm. rms emittance	0.35 mm mrad
Extraction gap	133 ns
Energy spread, 1 sigma	0.02%
Foil thickness	500 $\mu g/cm^2$
Hor./Ver. beta function at injection point	10 m/ 20 m
Hor./Ver. tune	8.24/8.31
Injection turns	481
Macro particles per turn	300
Pulse length per turn	1.2 μs
Beam intensity per turn	4.7×10^{11}
Dual-Harmonic RF voltage	5 kV/-2.5 kV
Barrier RF voltage	5 kV
Barrier RF phase	162 deg

Bump function

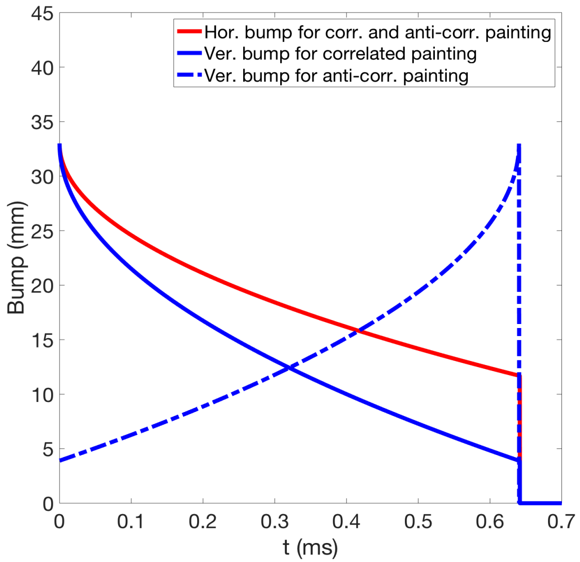
Case #1



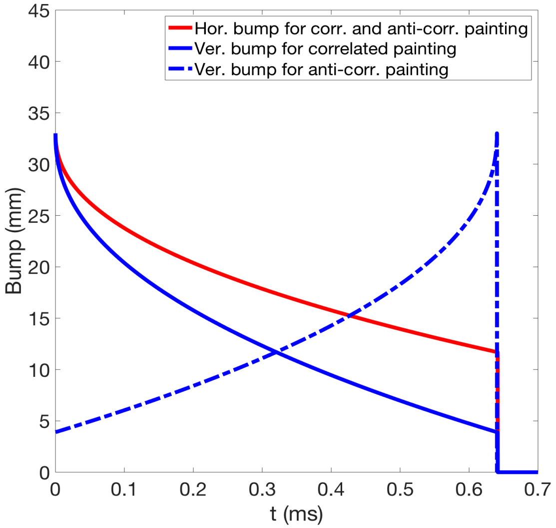
Case #2



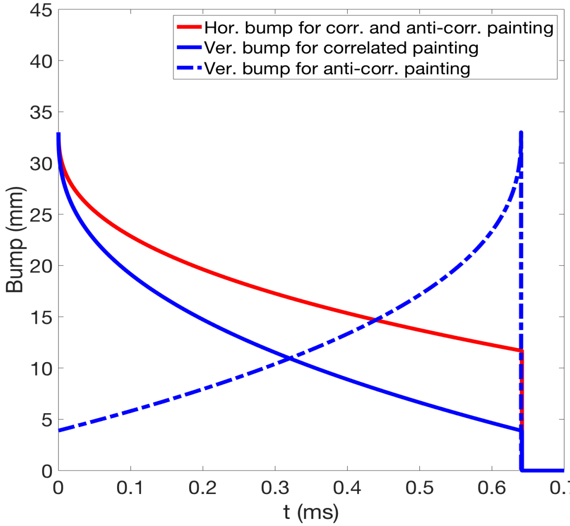
Case #3



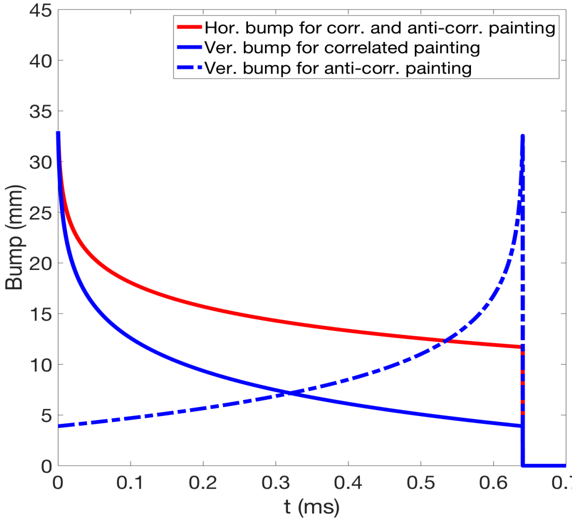
Case #4



Case #5

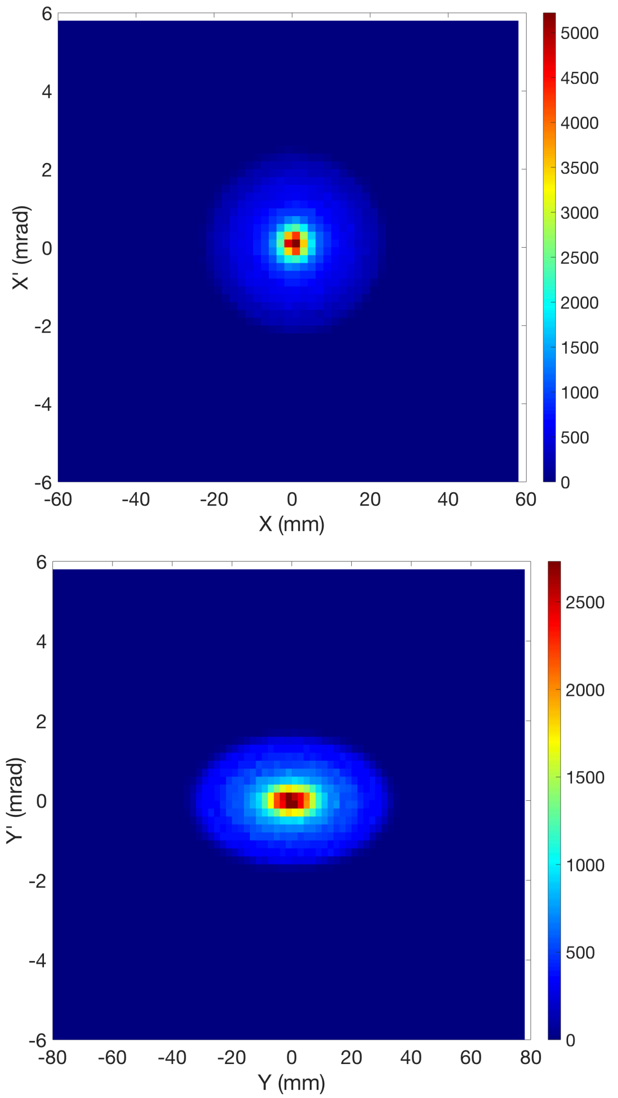


Case #6

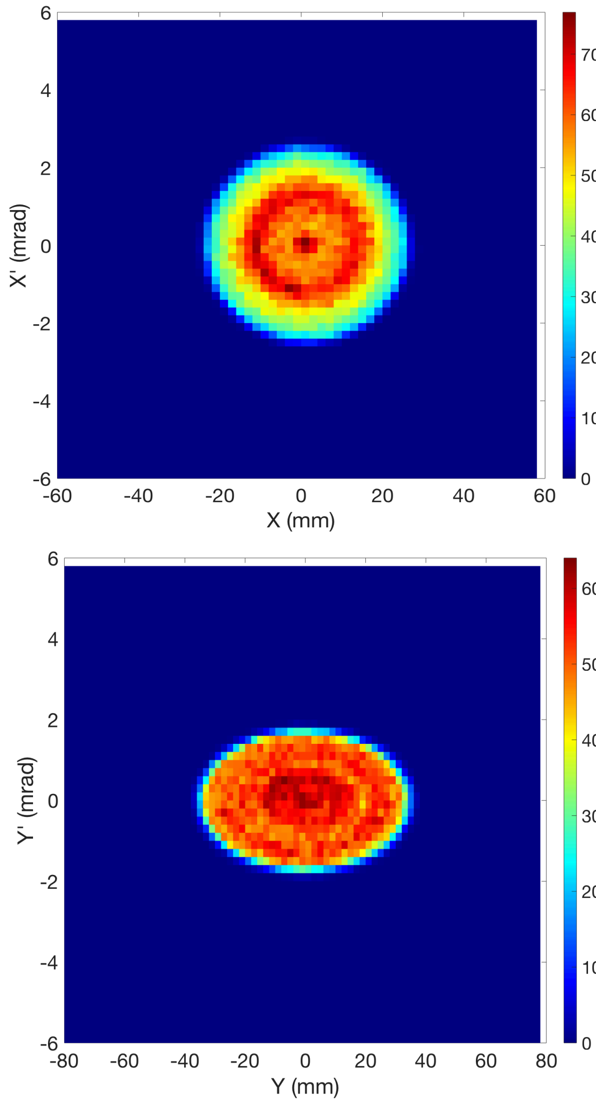


Beam distribution in transverse phase space (correlated painting)

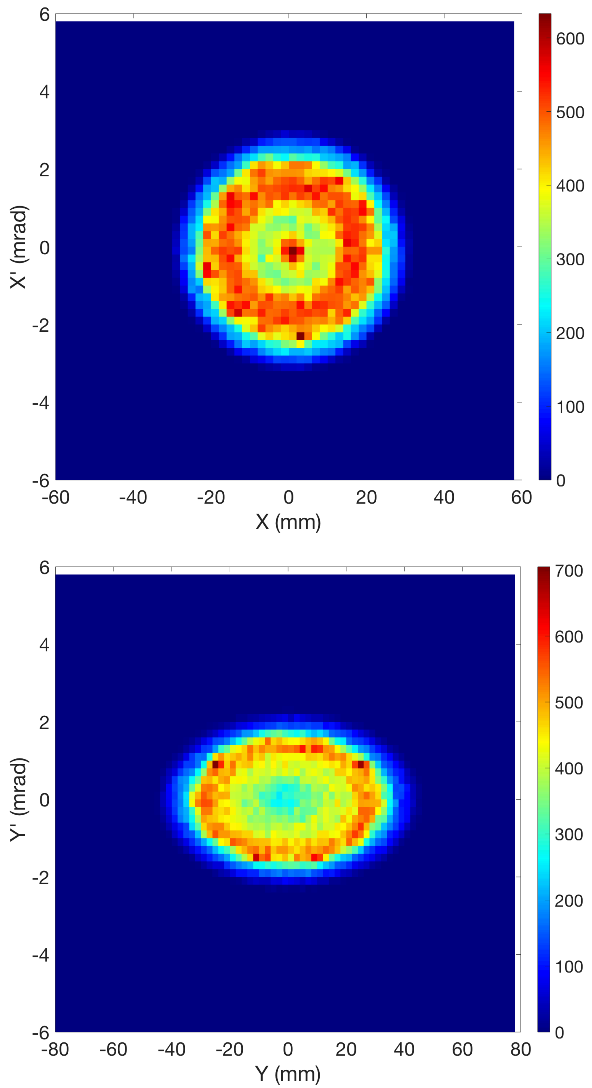
Less painting



Well painting

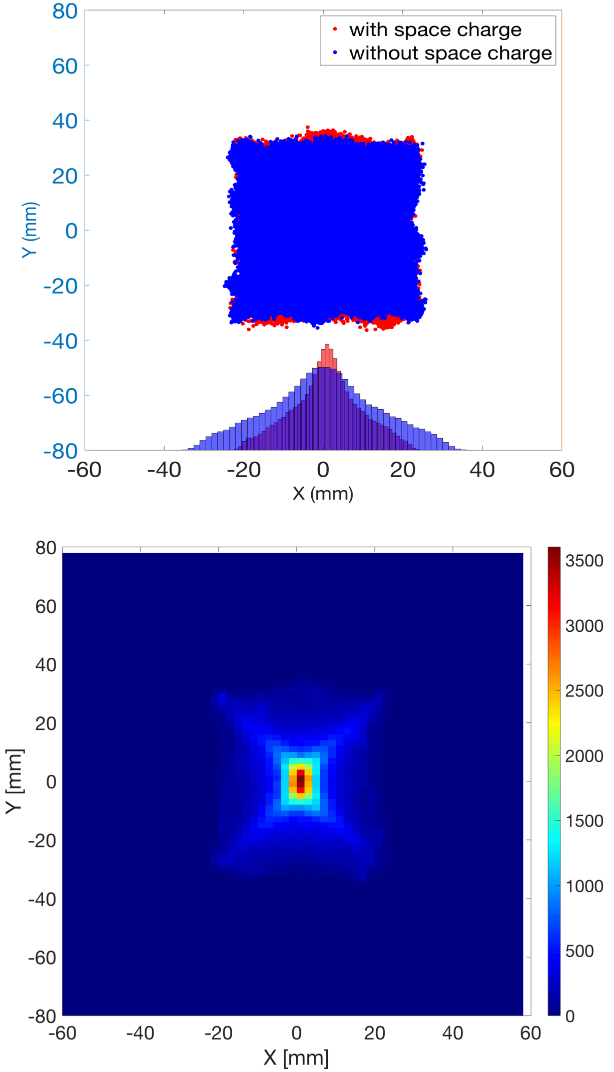


Over painting

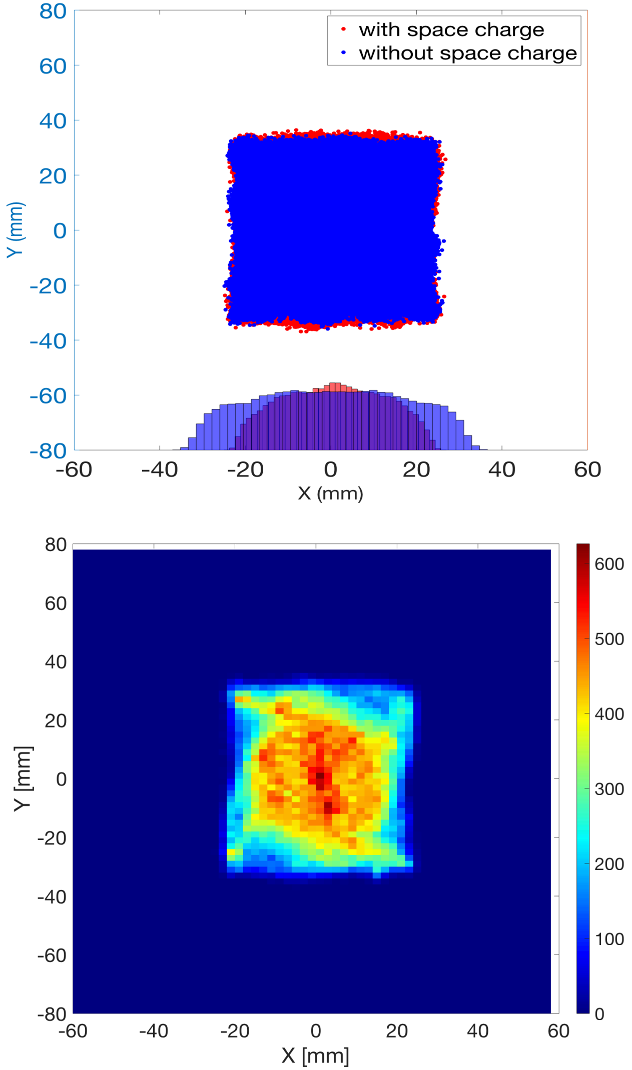


Beam distribution in real space (correlated painting)

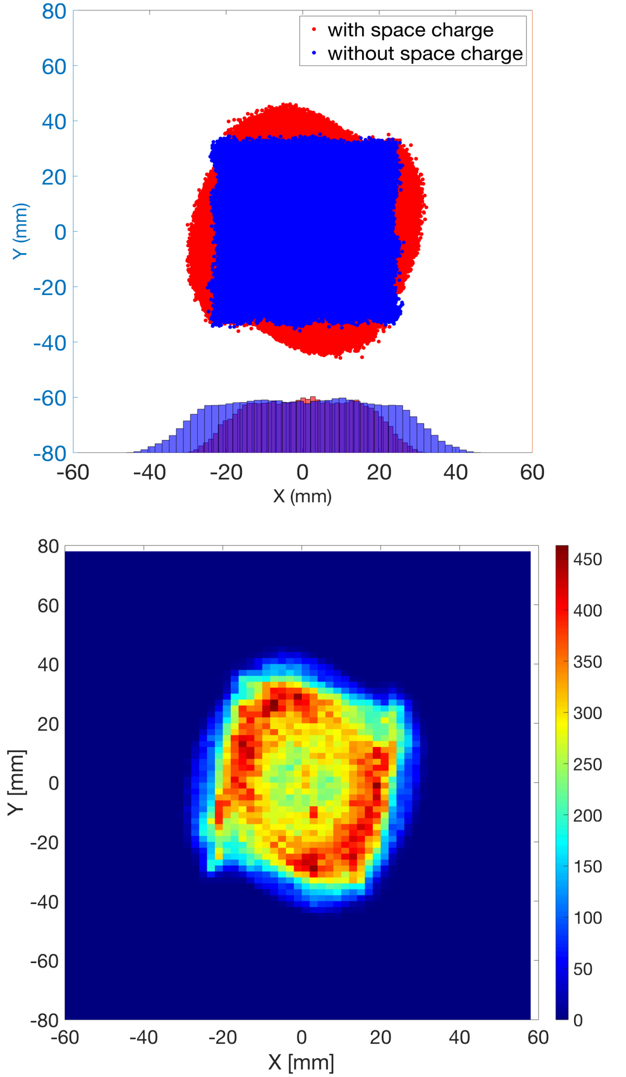
Less painting



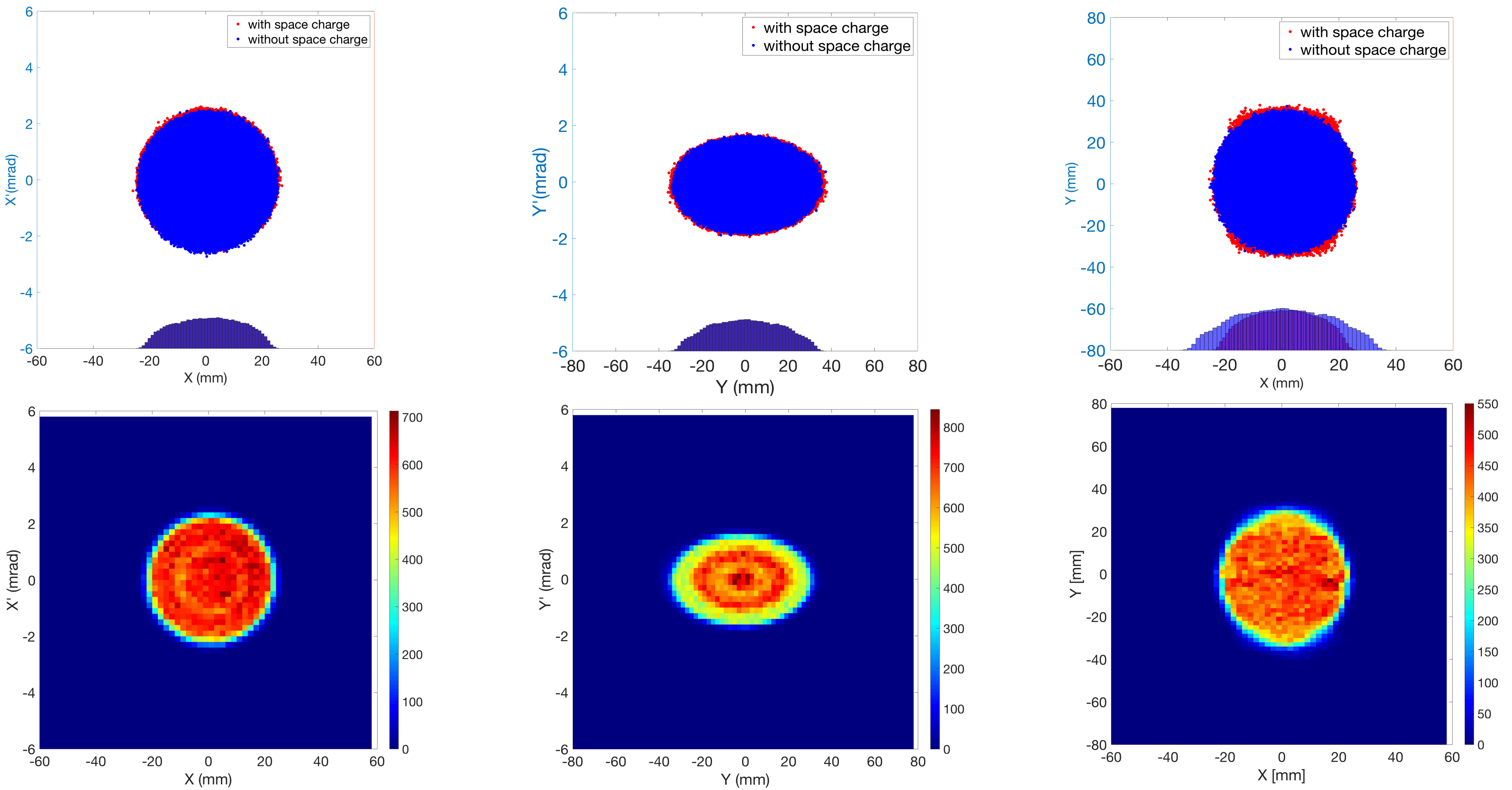
Well painting



Over painting



Beam distribution with anti-correlated painting (well painting)

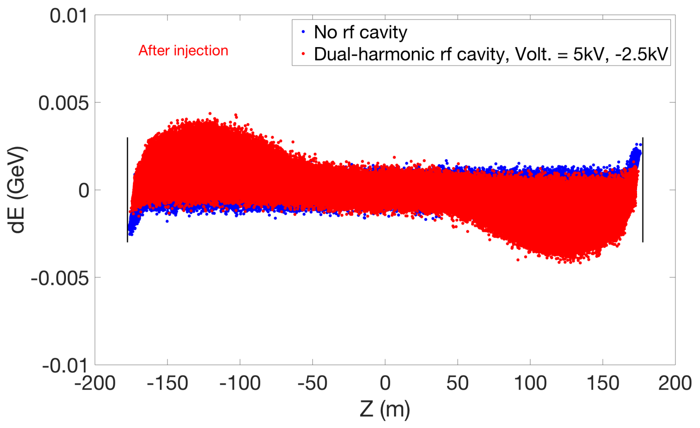


RF cavity and longitudinal beam distribution

Two main points

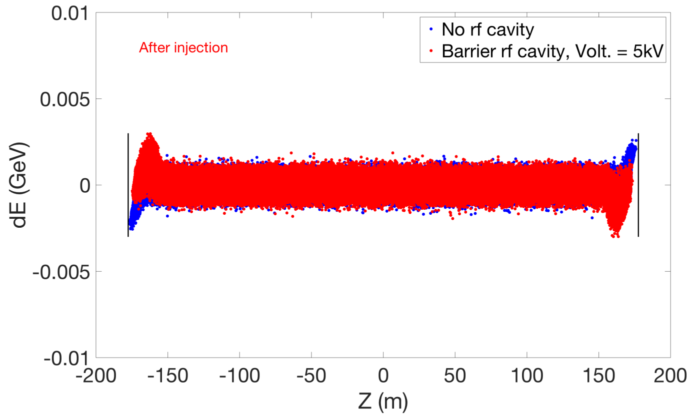
Point 1: Keep extraction gap clean during the whole accumulation process
Point 2: Minimize the energy spread

Dual Harmonic RF cavity
(Low voltage, 5kV)

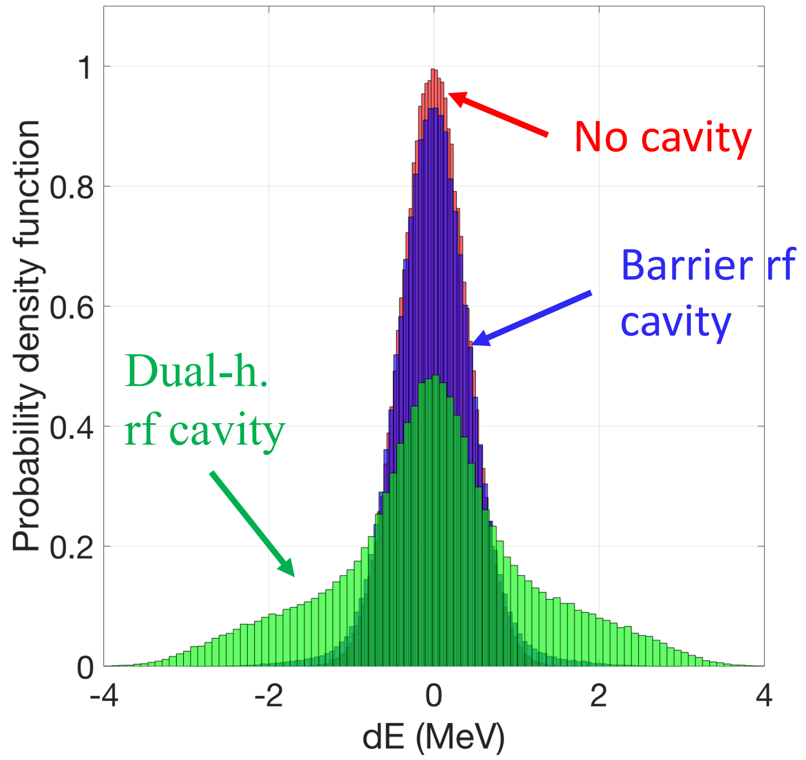


Point 1: small risk to leak
Point 2: excellent (~ ±0.2%)

Barrier RF cavity

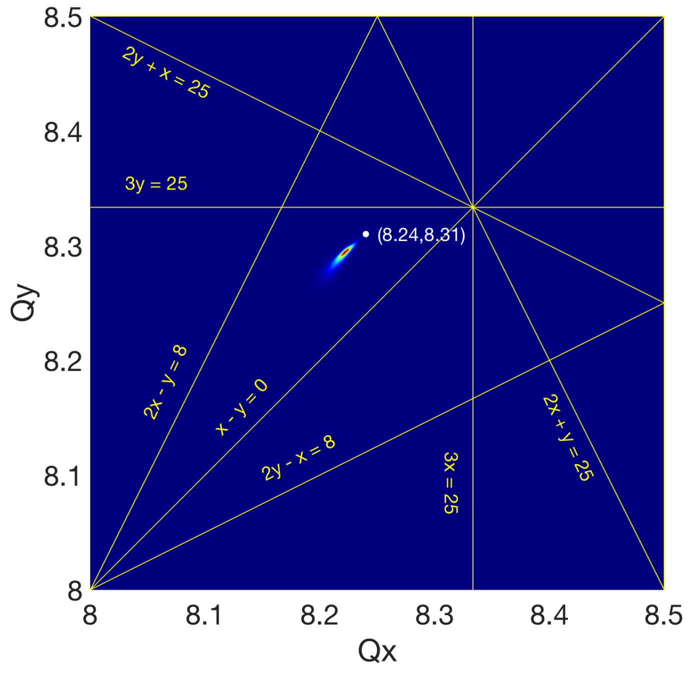


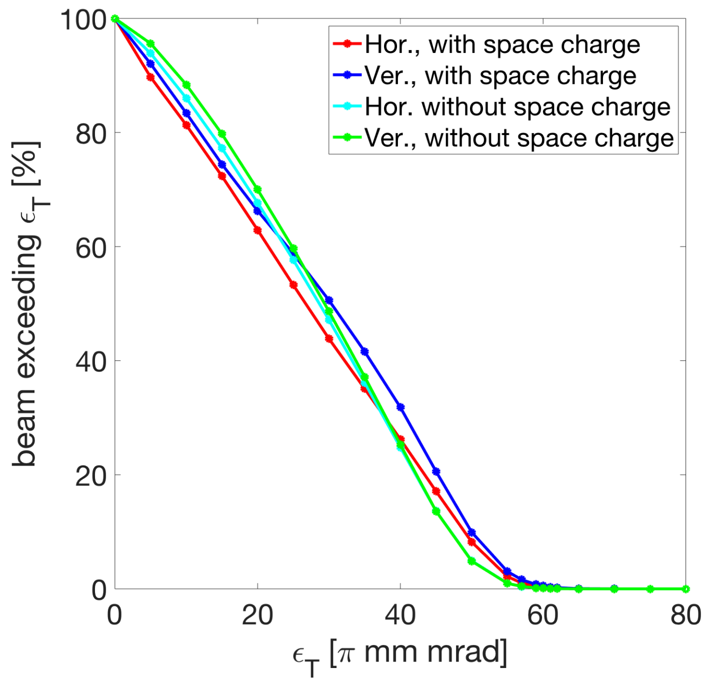
Point 1: excellent
Point 2: excellent (~ ±0.15%)

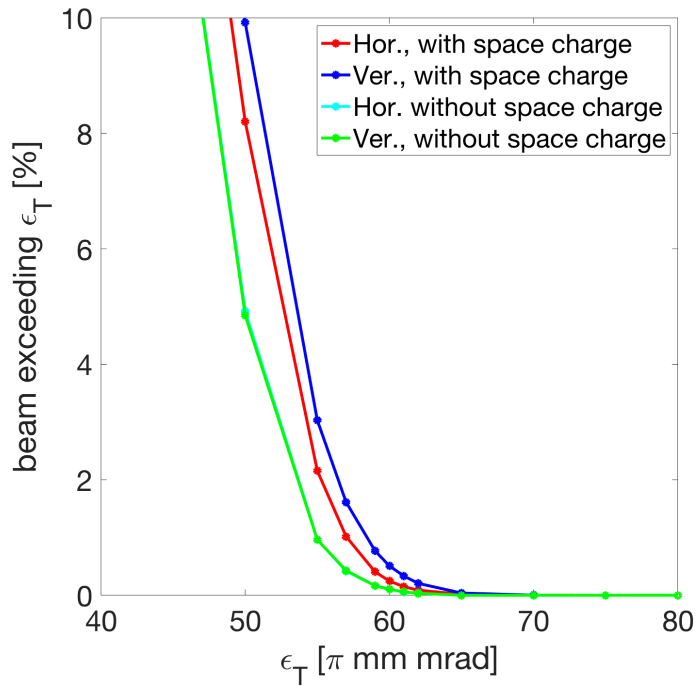


- Beam is quite stiff
- Particles leakage to the gap would be possible without RF cavity
- Small risk to leak and small energy spread if dual harmonic rf cavity with low voltage (~5kV)
- Very small risk to leak and very small energy spread if barrier rf cavity implemented

Tune and Emittance (correlated painting)

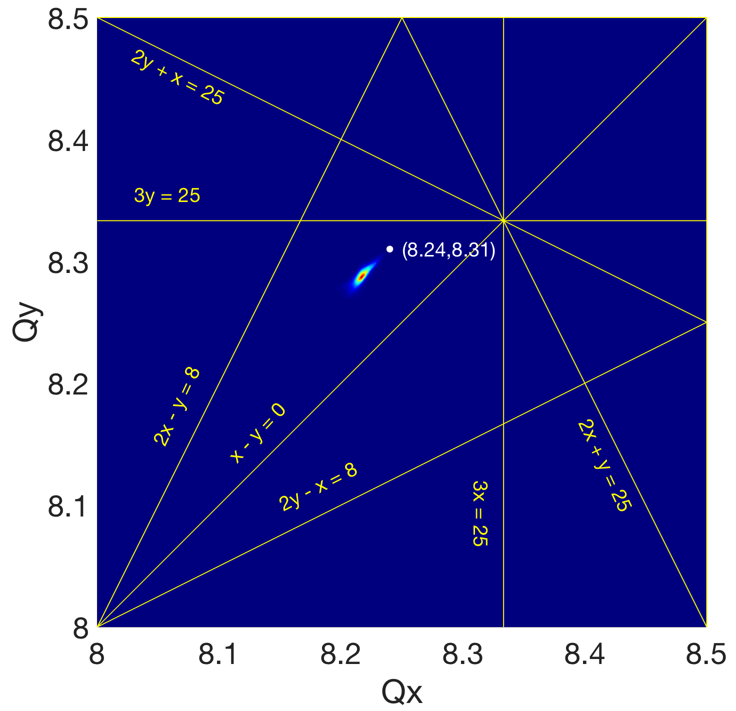


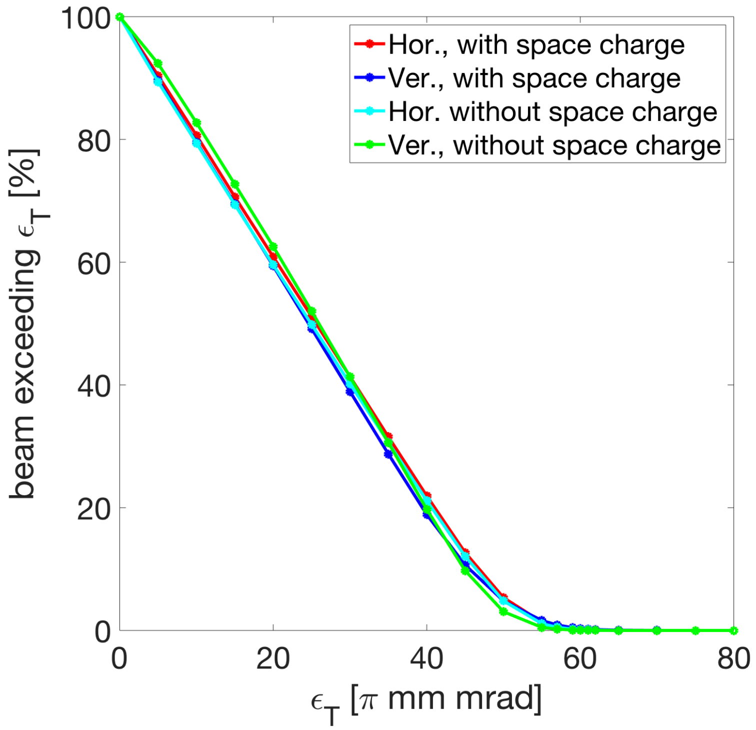


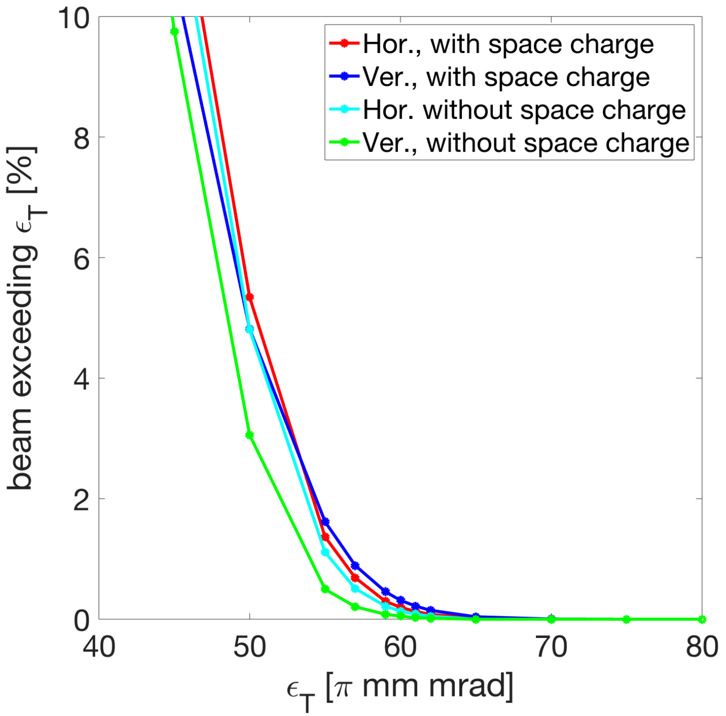


- Very small tune spread (~0.05), which fits the calculation results
- 99.7% beam emittance: about 60 π mm mrad in horizontal and 61 π mm mrad in vertical plane
- RMS emittance: 13.5 π mm mrad in horizontal and 14.5 π mm mrad in vertical plane

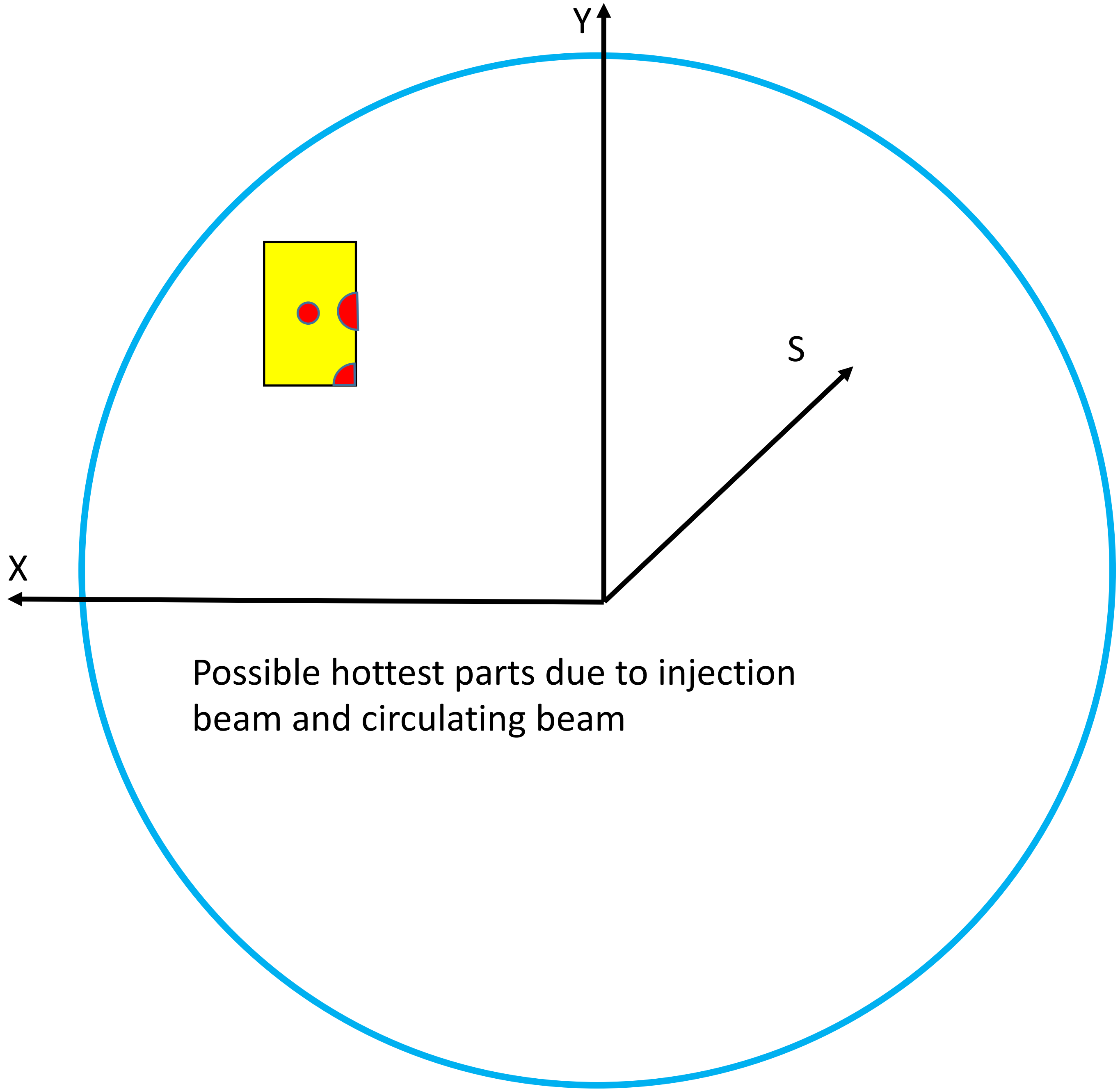
Tune and Emittance (anti-correlated painting)



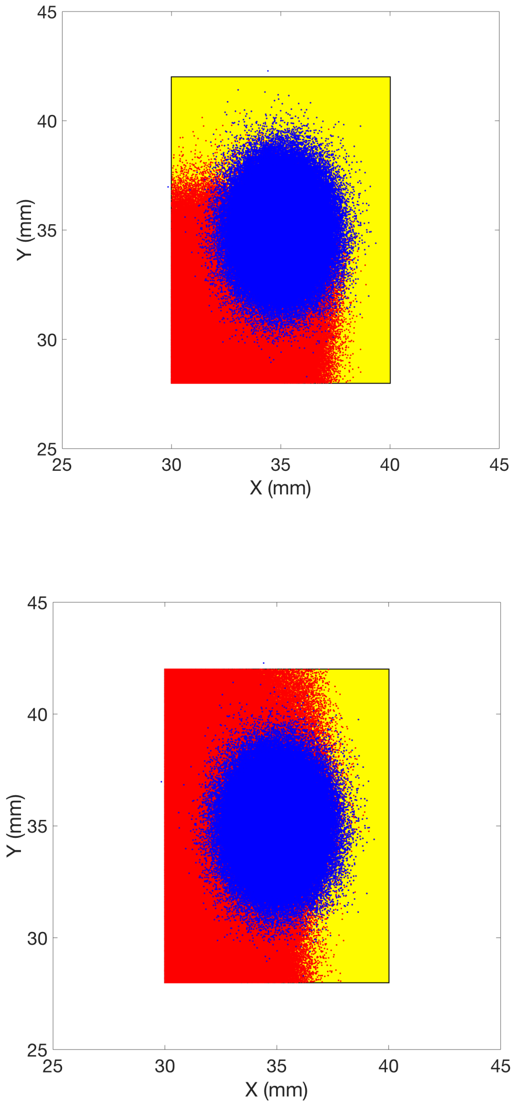




- Very small tune spread (~0.05), which fits the calculation results
- 99.7% beam emittance: 59 π mm mrad in horizontal and 60 π mm mrad in vertical plane
- RMS emittance: 12.9 π mm mrad in horizontal and 12.5 π mm mrad in vertical plane



Possible hottest parts due to injection beam and circulating beam



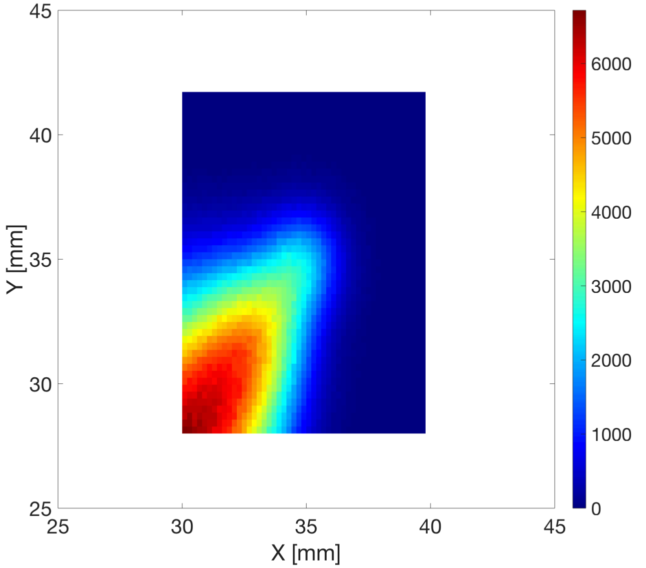
Injection beam (Blue) and circulating beam (Red) distribution on the foil (Upper: corr. Painting; lower: anti-corr. painting)

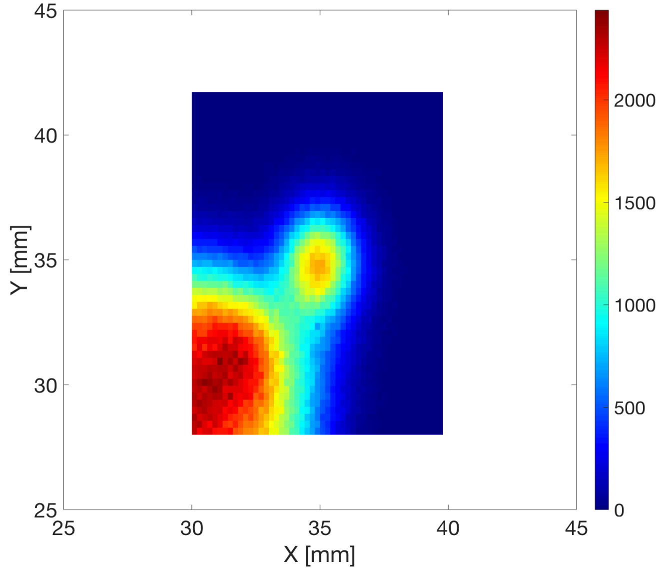
Beam foil-hits distribution

Case #1

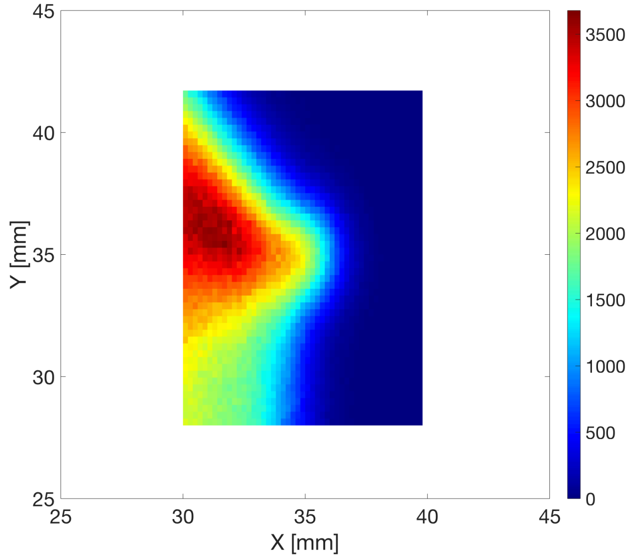
Case #5

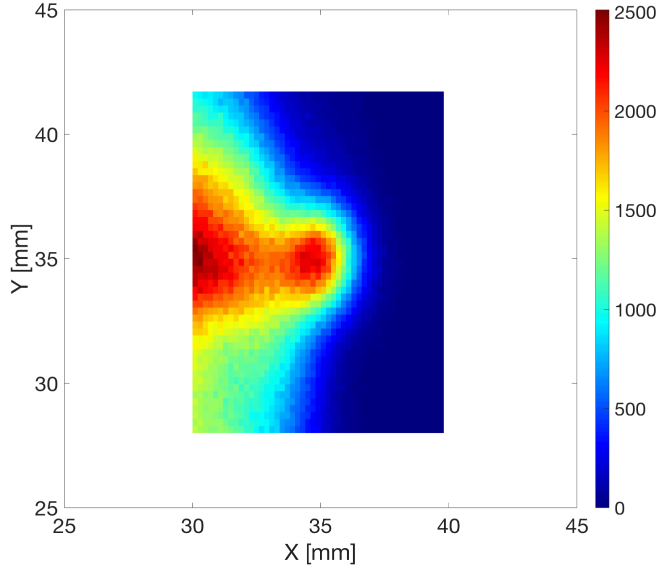
Corr. painting





Anti-corr. painting

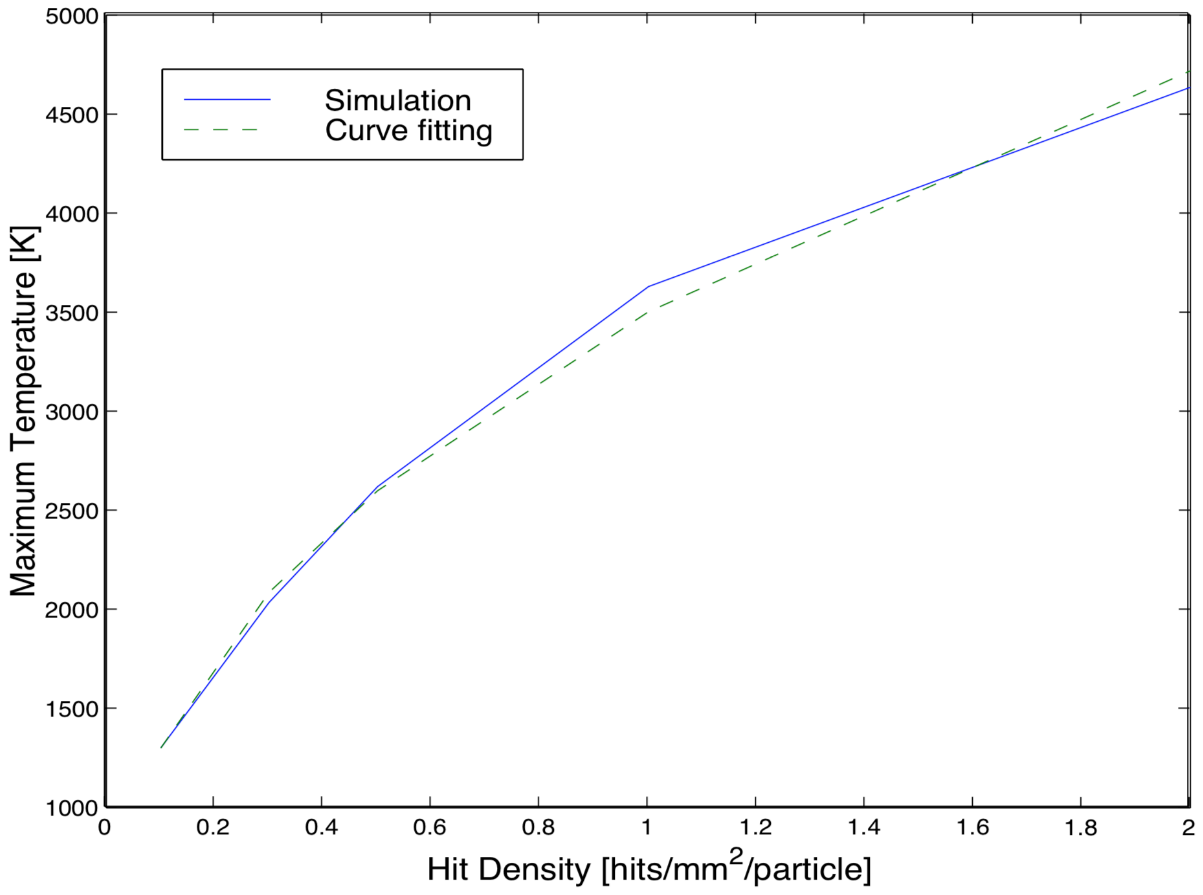




Foil temperature calculation

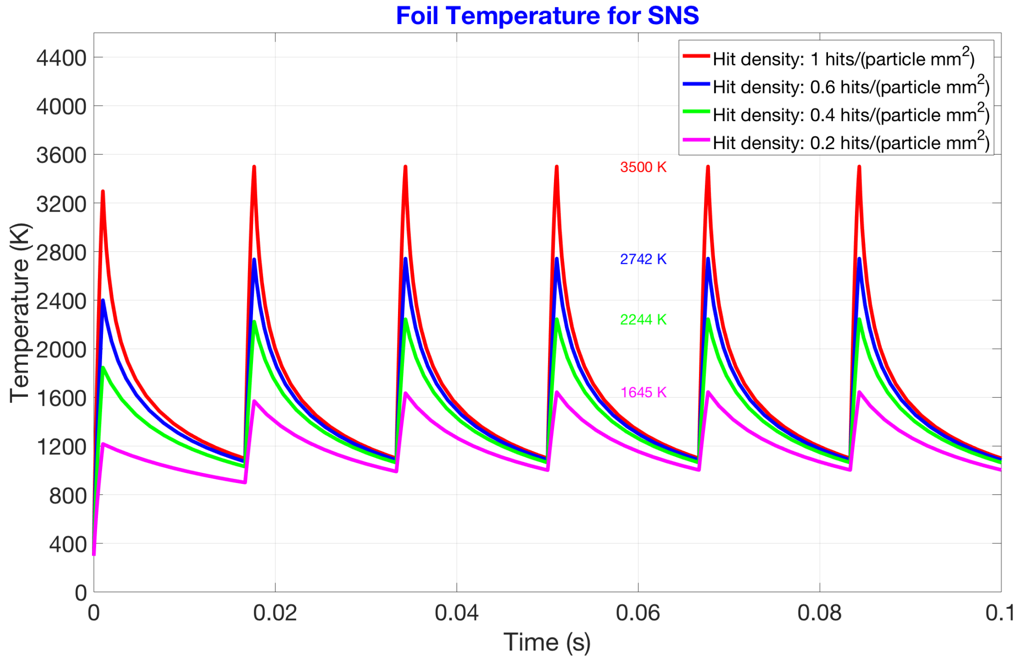
- A simple MATLAB code is developed to estimate foil temperature
  - Radiative cooling is considered, assuming no cooling via conduction
  - Carbon foil is chosen and the emissivity is chosen to be 0.8
  - Heat capacity is from: C.J.Liaw 1999, http://accelconf.web.cern.ch/Accelconf/p99/PAPERS/THP143.PDF
  - Electrons contribution on the foil heating is also taken into account, 0.84 reduction due to knock-on electrons according to Mike Plum's studies
  - Code benchmark with SNS results when inputting SNS configurations
- Several methods are considered to mitigate the peak temperature on the foil:
  - Optimizing the bump function can mainly decrease the peak foil temperature at inner corner
  - Splitting the foil into several thinner ones with the same total thickness can lower the peak temperature at both center and corner if the foils are separated with enough distance in order to minimize the affect between each other
  - Moving injection point or adopting several foils along horizontal plane is also considered

Code benchmark with SNS results



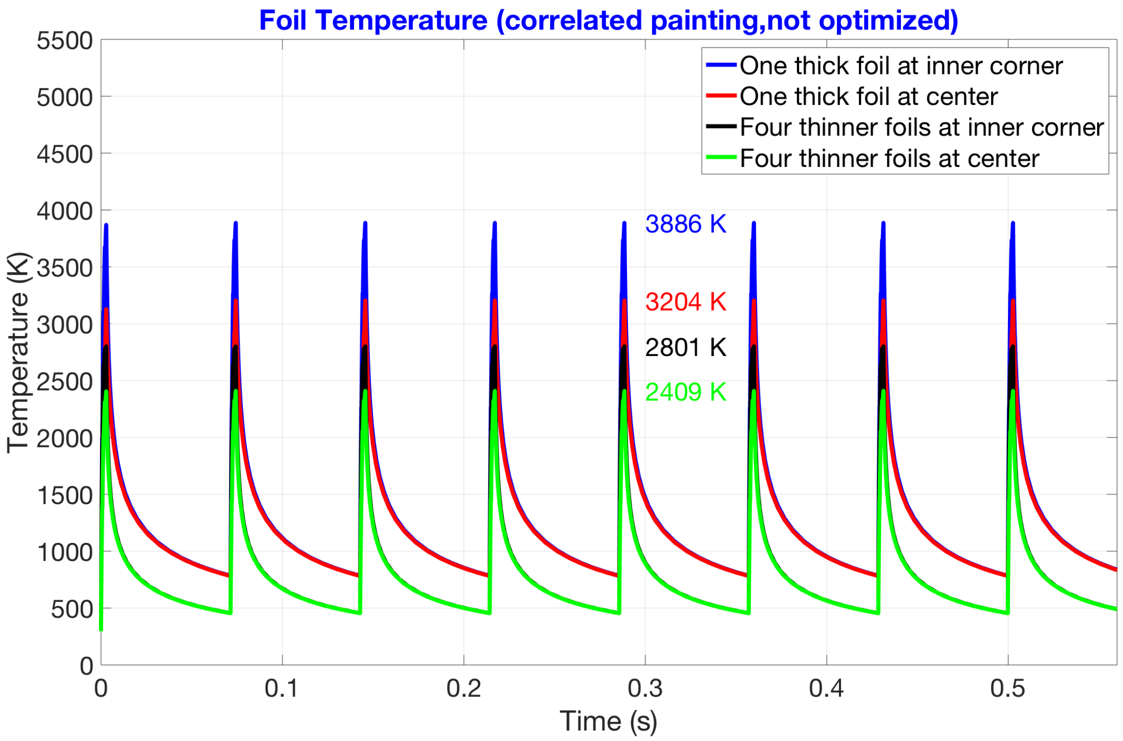
J. Beebe-Wang et.al., BNL, proceedings of 2001 PAC Chicago, USA

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

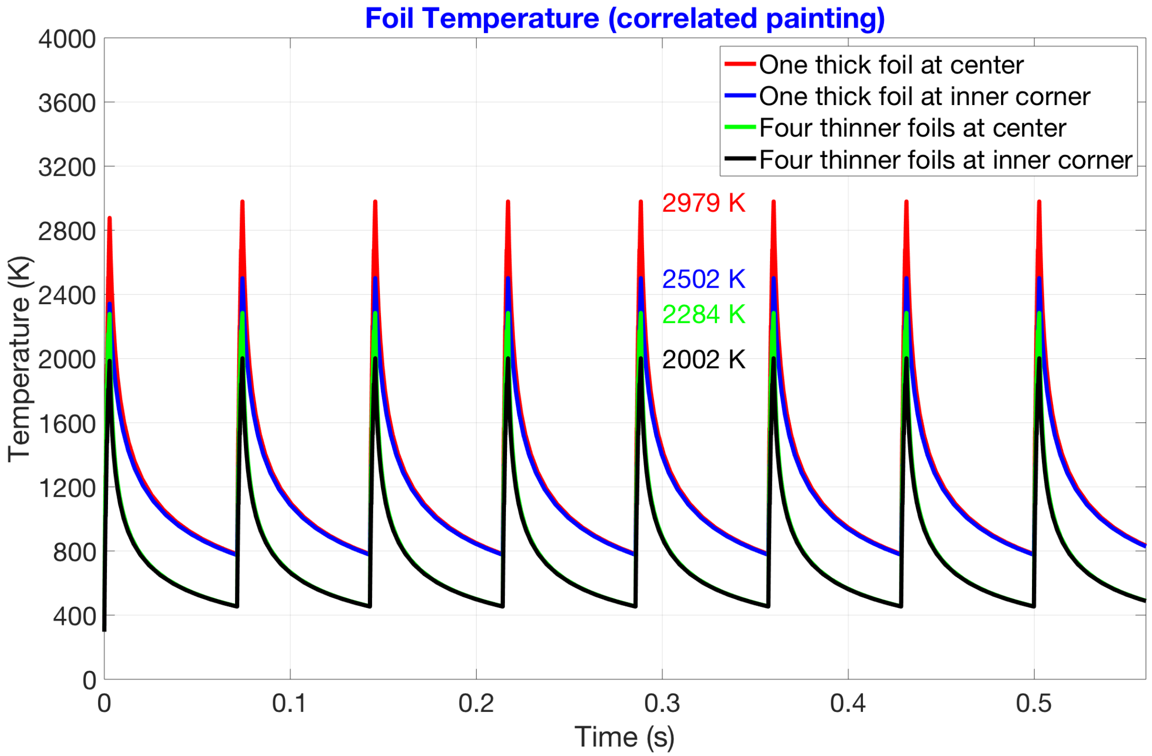


Foil temperature (correlated painting, 28 Hz)

Not optimized

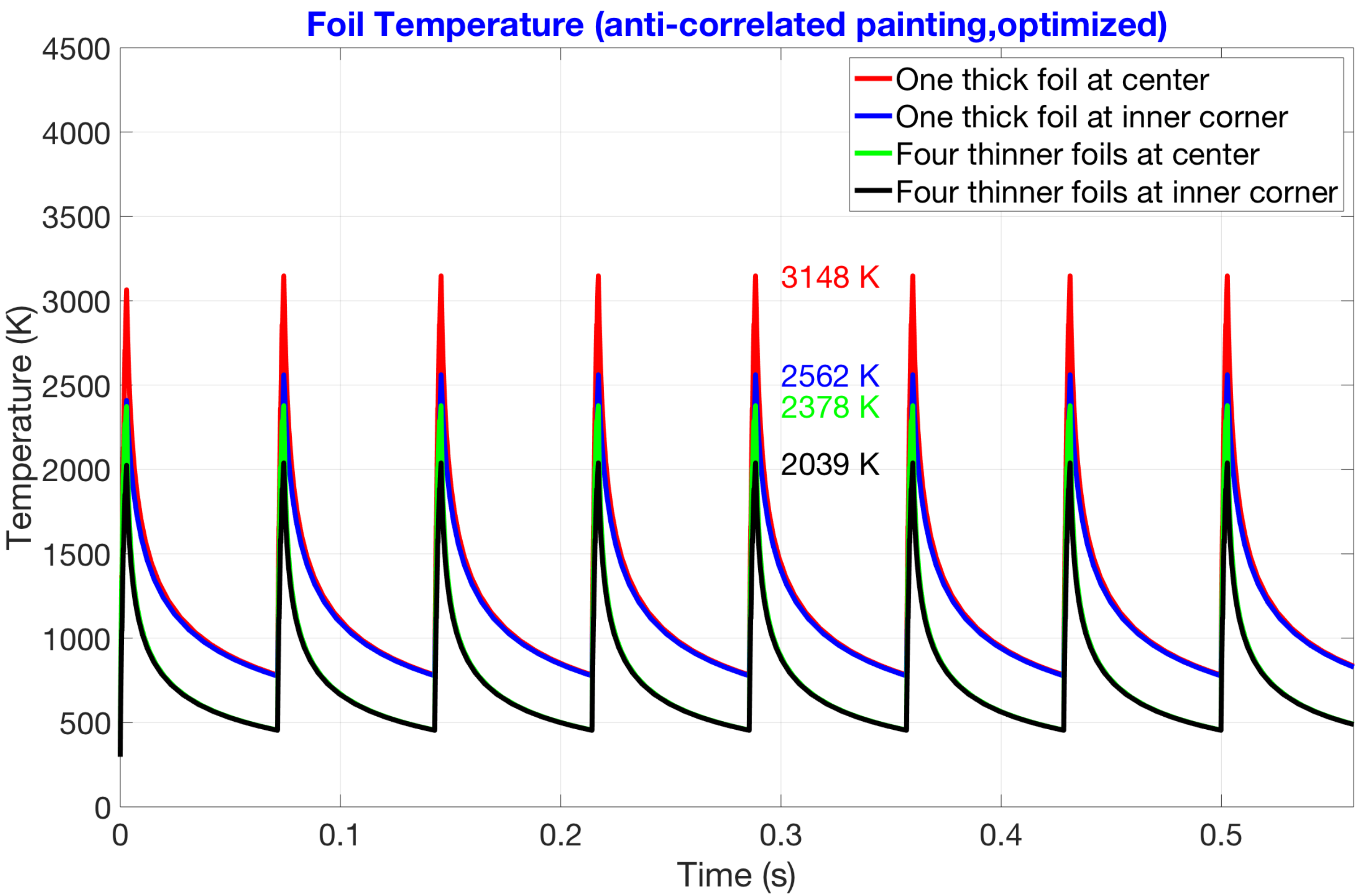


Optimized



- Optimizing bump function can lower foil temperature at inner corner very efficiently
- Several-thinner-foils scheme is an effective way to mitigate the maximum temperature issue on the foil.

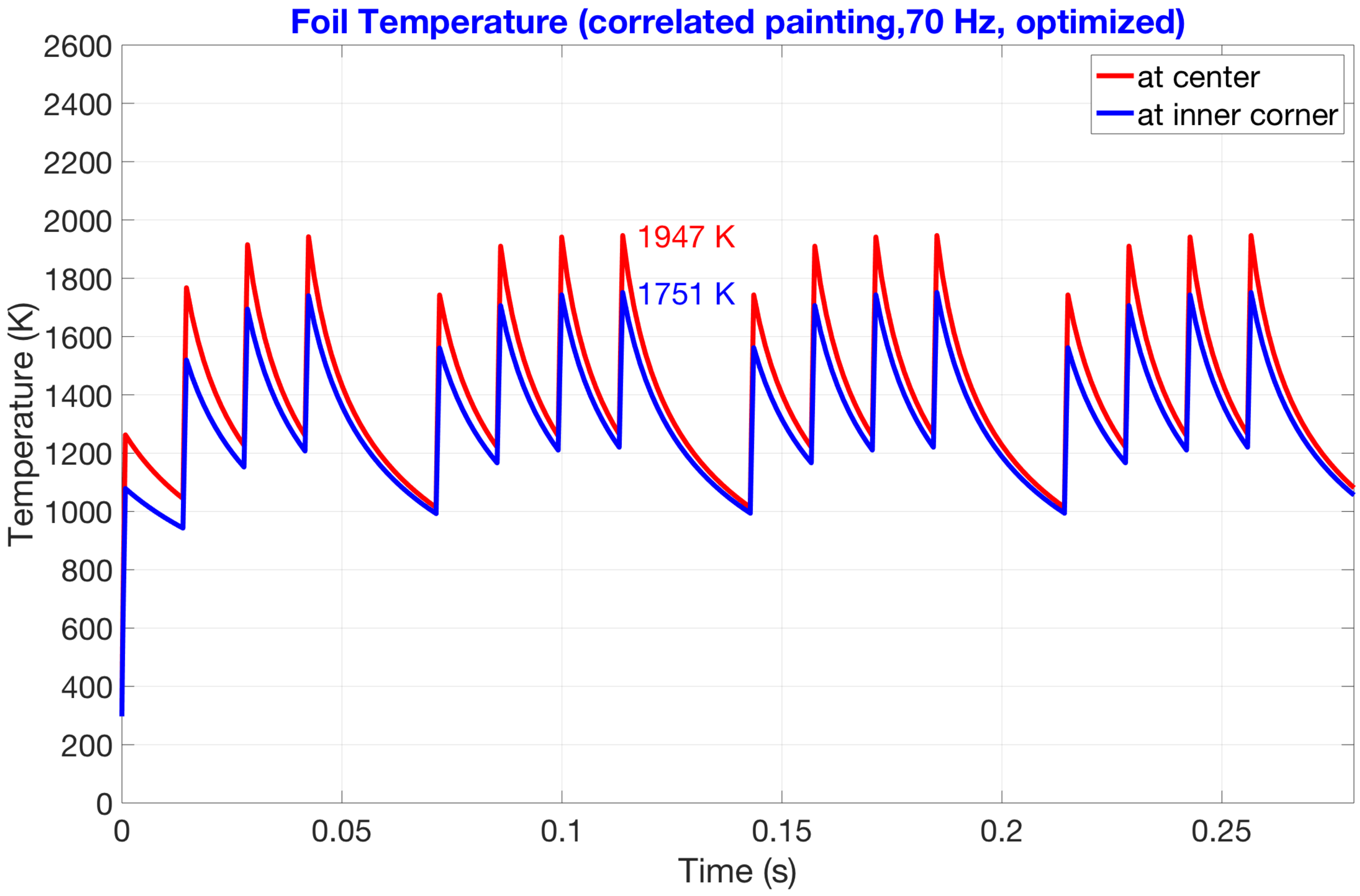
Foil temperature (anti-correlated painting, 28 Hz)



With different number of thinner foils

# of thinner foils	Thickness of each foil (ug/cm^2)	Correlated painting		Anti-correlated painting	
		Temperature at center (K)	Temperature at corner (K)	Temperature at center (K)	Temperature at corner (K)
1	500	2979	2502	3148	2562
2	250	2631	2255	2749	2298
3	167	2427	2103	2534	2138
4	125	2284	2002	2378	2039
5	100	2175	1914	2250	1947
6	83	2088	1853	2157	1883
7	71	2016	1789	2091	1818
8	63	1945	1747	2015	1773
9	56	1892	1703	1970	1722
10	50	1855	1665	1915	1689

Foil temperature (correlated painting, 70 Hz, optimized)



Summary and outlook

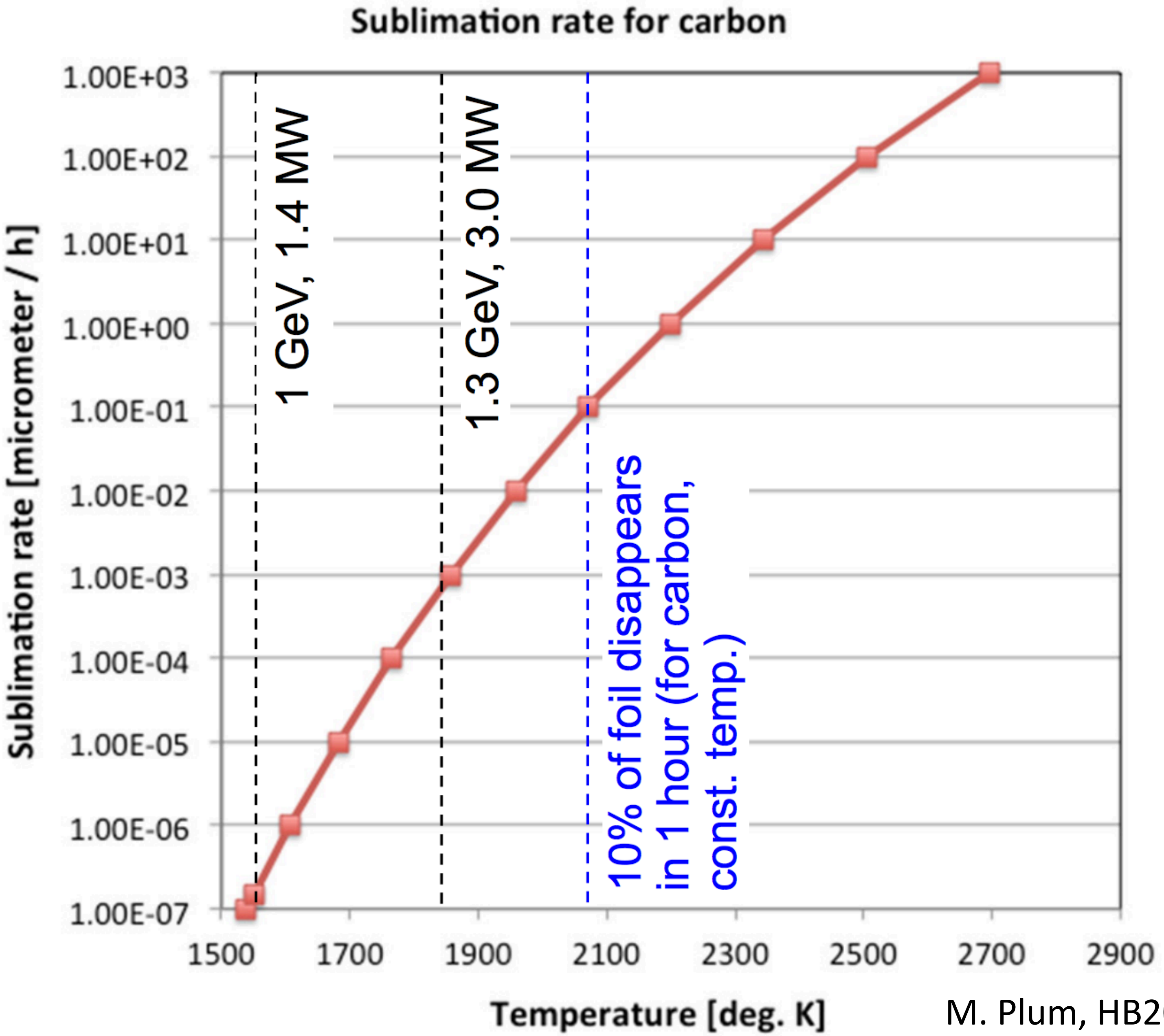
Where we are now:

- Paint to quite uniform distributions with 100% emittance ~60 π mm mrad
- Space charge tune shift: ~0.03
- Extraction gap kept clean well
- Foil temperature issues can be mitigated in several ways and still in progress

What we plan to do

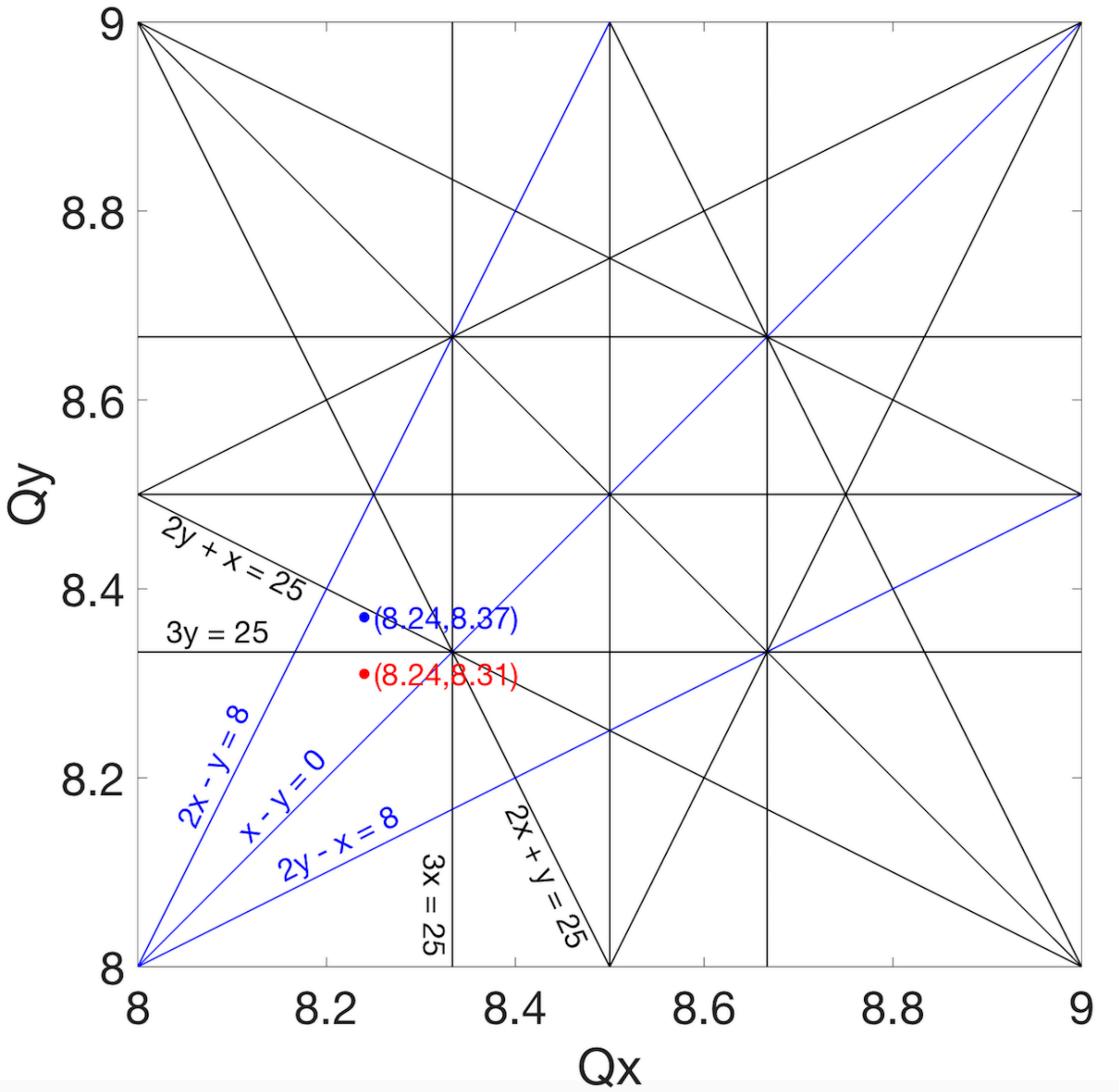
- Collimation system design
- Chromaticity correction
- Dynamic aperture studies

Back-up slides



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

Resonance and superperiods



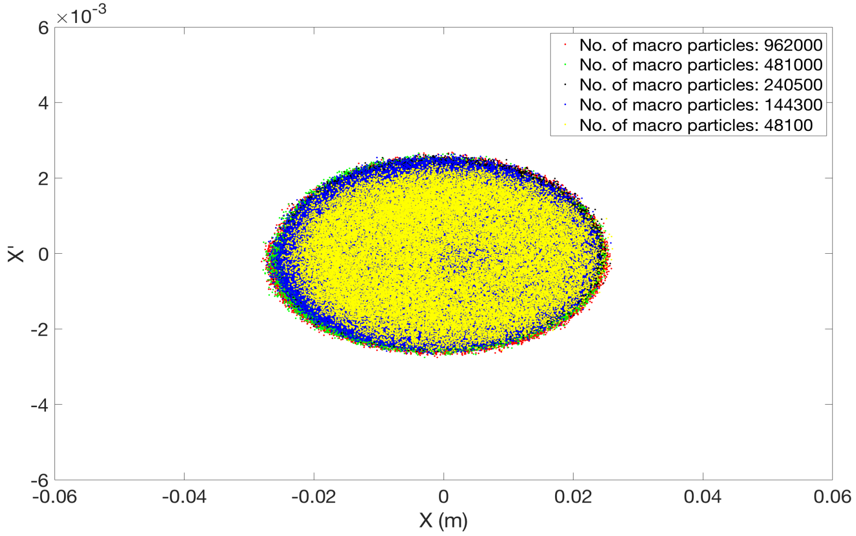
- Tune spread induced by space charge effect, natural chromaticity, and magnet imperfection is unavoidable.
- Tune spread should be far from each order of resonance, in particular, low order resonance (<=3) due to possible beam loss
- Space-charge tune shift requirement: < 0.2
- Transverse resonance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

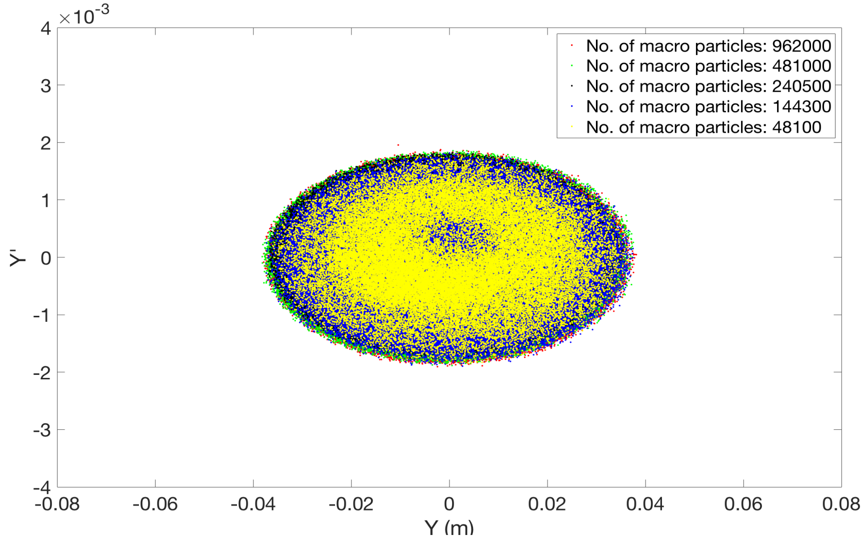
$$m\nu_x + n\nu_y = iN$$

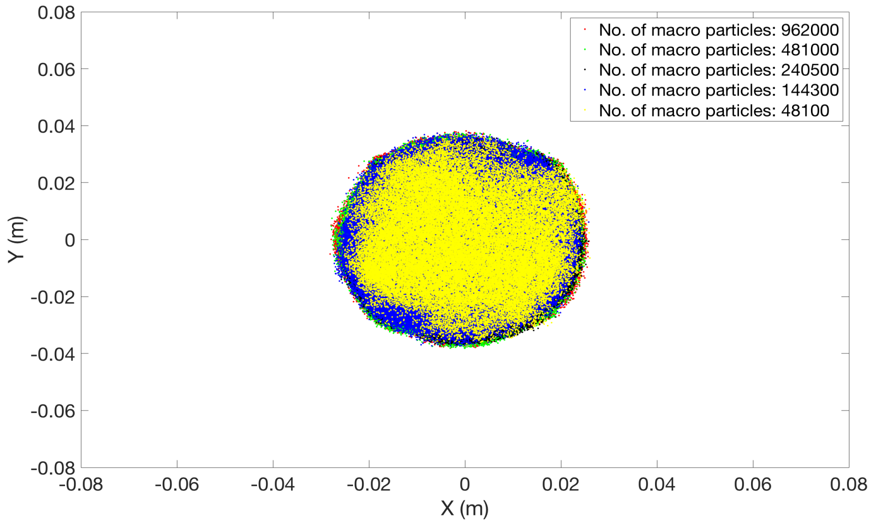
m,n,i,N integers, $l = |m| + |n|$ is the order of resonance, *N* is superperiodicity number.

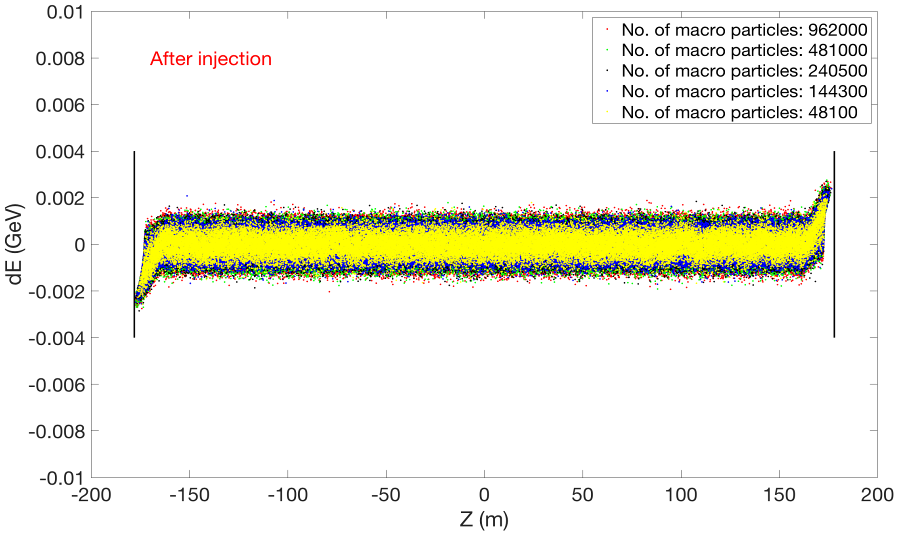
- If *N*=1, black and blue lines;
- if *N*=4, only blue lines
- A higher superperiodicity is better

Convergence study







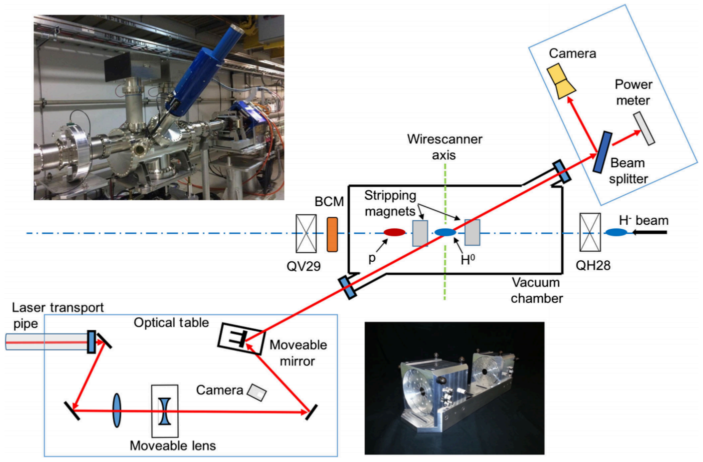


300 macro particles per turn for injection is good enough for numerical simulation.

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