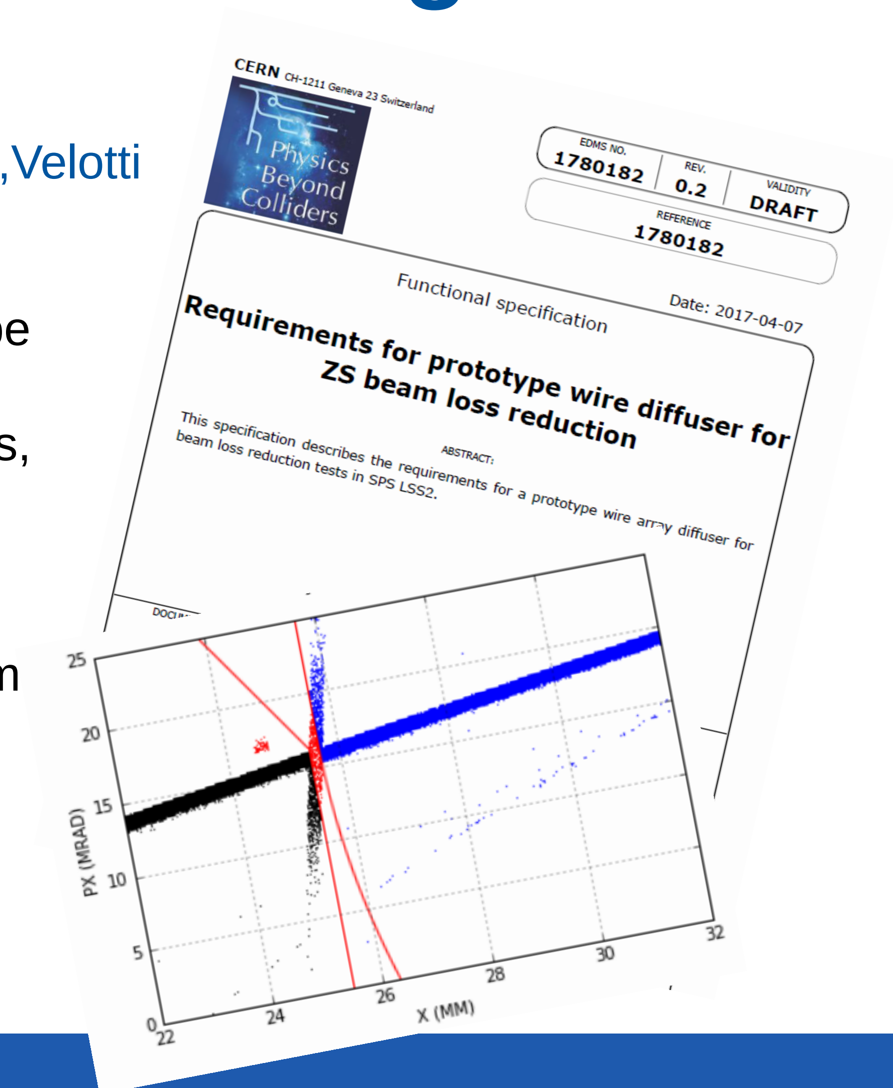
CERN

Passive diffuser studies and design

B.Balhan, D.Barna, J.Borburgh, M.Fraser,
B.Goddard, L.S.Stoel, P.van Trappen, F.M,Velotti

A passive scattering device (diffuser) can be used to reduce septum beamloss. The talk describes the underlying physics processes, and investigates the dependence on the diffuser geometry, material and location. Numerical simulations to quantify the expected performance gain for the optimum configuration are presented, and the progress with the realisation of a prototype for deployment in the SPS presented.



Outline

- Diffuser basics
- Optimisation of materials and geometry
- Performance expectations
- Prototype design
- 2018 test plans
- Conclusions

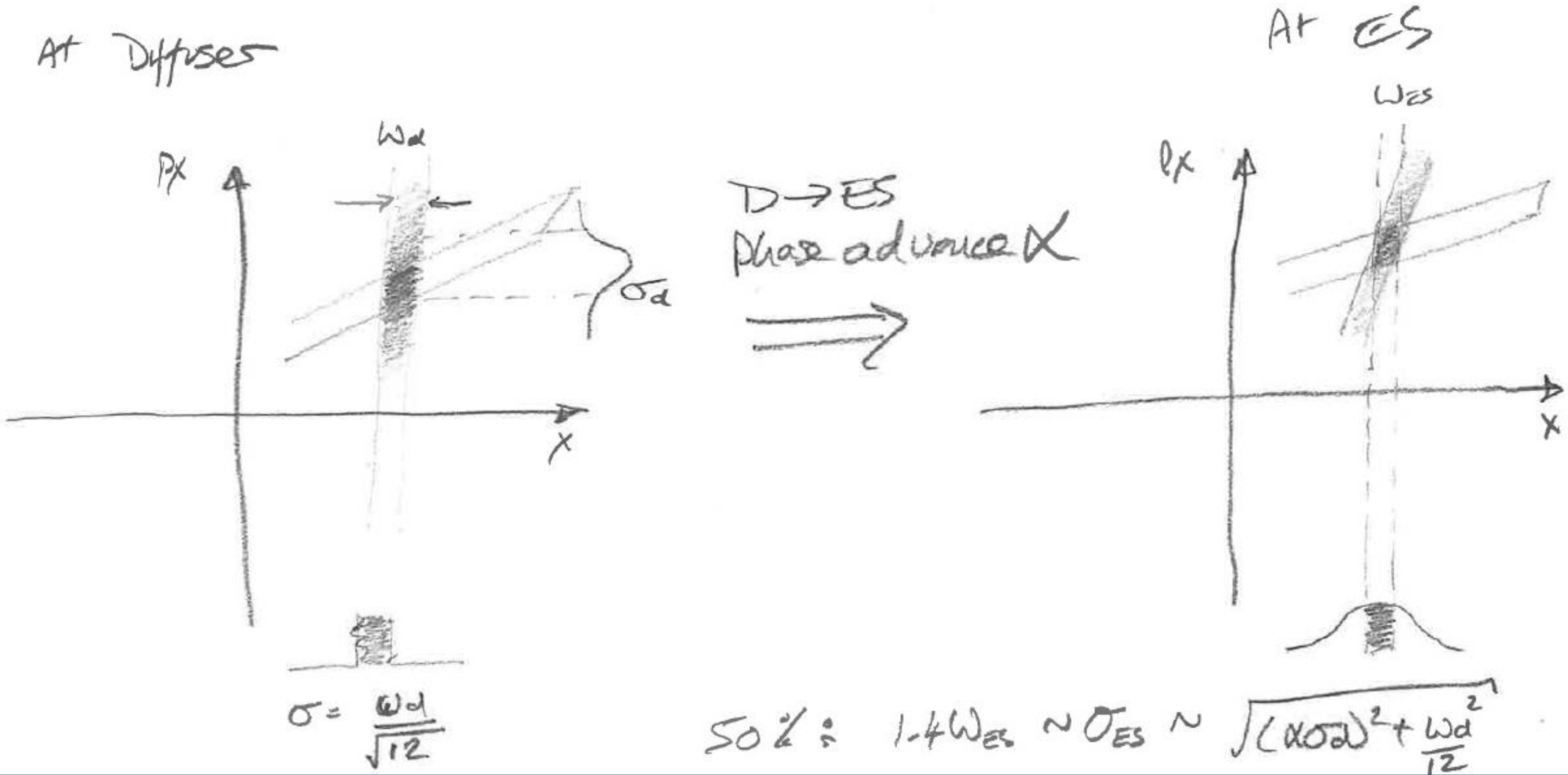
Passive diffusers (pre-scatterers)

- Diffuser/pre-scatterer has been studied for many decades [1-4].
- 0.3 m long WRe wire diffuser is used upstream of the 1.8 m Mo foil septum SEH31 in CERN PS since 1970s.
- FNAL is actively looking into using diffuser. They intent to use Ti foil upstream of their ES [5], i.e. 0.5 m diffuser followed by 1.25 + 1.75 m of wire septa.
- We understand J-Parc experimented in past with Carbon wire diffusers [6]:
  - initially 7µm strands were twisted to obtain 120 µm wires
  - nanotube Ø 50 µm twisted to obtain 125 µm wires.
- New SPS diffuser [7] being built to install end 2017, for 2018 beam tests

PS diffuser upstream of foil septum

Basic idea

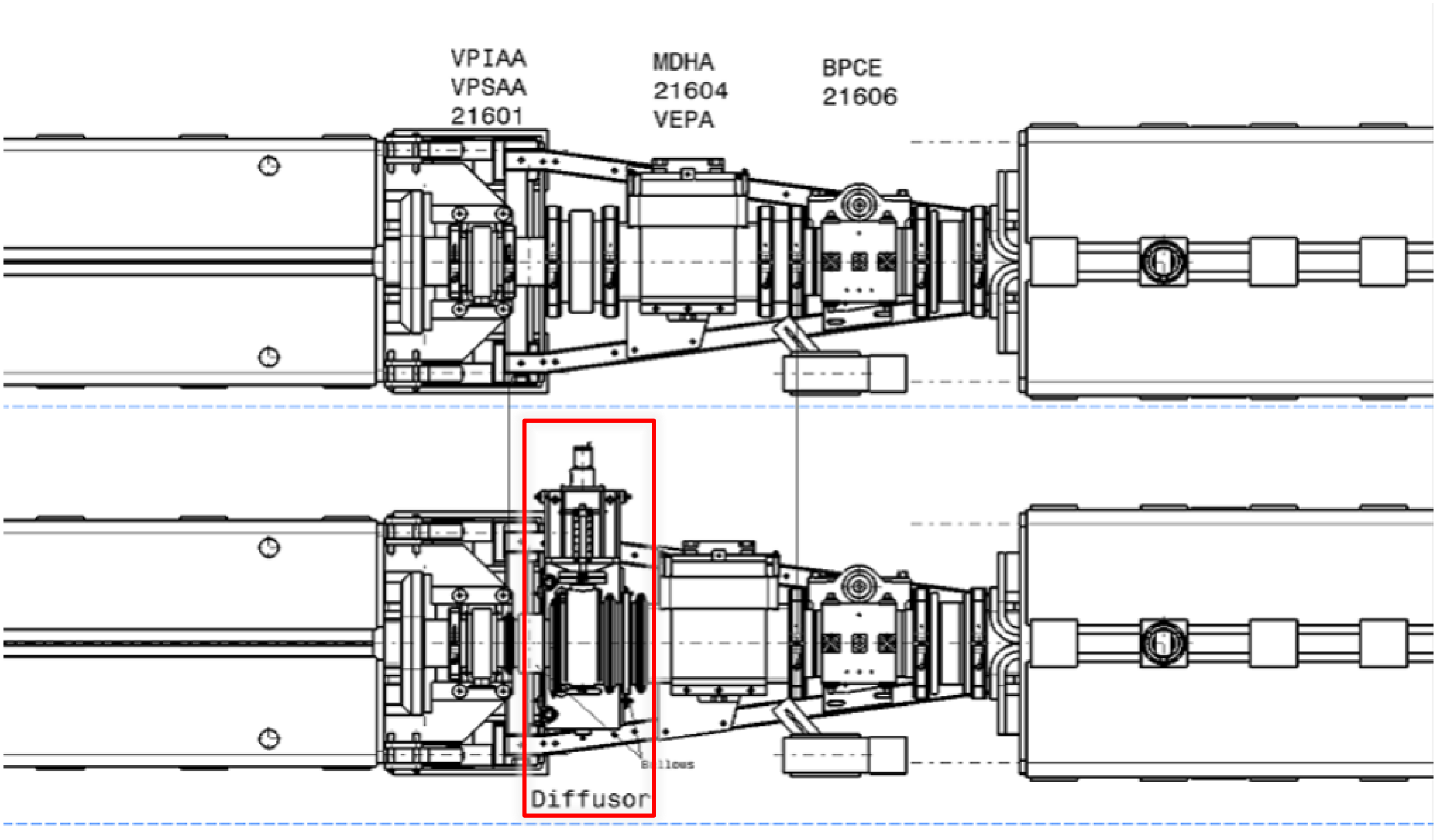
- Generate angular spread upstream of ES, with enough phase rotation to transform the angular spread into position spread



Local or non-local?

- Could place far away from ES, to optimize phase advance
  - Needs local bump, separate instrumentation, activates another region, stability concerns….
- Opt for local diffuser for SPS, just upstream ES
  - Keeps system inside single bump
  - Profit from improved control of separatrix (dynamic bump)
  - Keep losses localised in LSS2
  - But no choice of phase advance: basically fixed at 3.2°

SPS implementation – 5 m upstream of ES



Estimate of required scattering angle

- For a (small) diffuser-ES phase advance α, and diffuser width w_d the normalised MC angle spread Θ_o generated by diffuser transforms into a normalised position spread σ_x at the ES of

$$\sigma_x \approx \left(\alpha^2\Theta_o^2 + w_d^2/12\right)^{1/2}$$

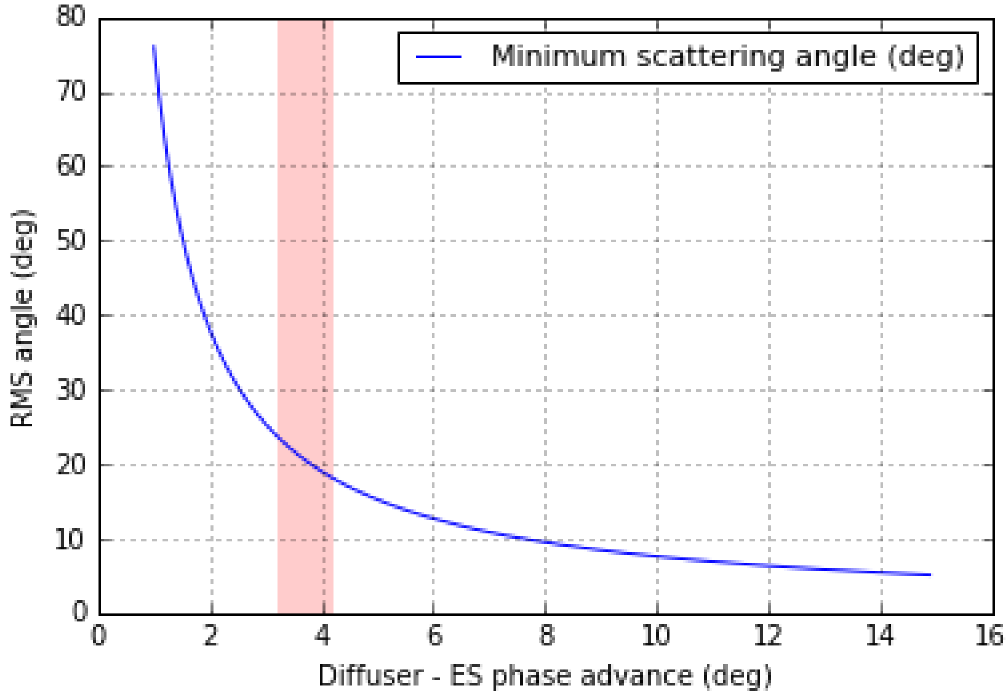
To achieve a factor 2 loss reduction, ES width w_{ES} should be maximum of about $\sqrt{2}\,\sigma_x$

  - (Actually it will need to be smaller, as this neglects losses in diffuser and effective ES width)

- As rough condition

$$\Theta_o > \left(\frac{w_{ES}^2}{2\alpha^2} - \frac{w_d^2}{12}\right)^{1/2}$$

~25 urad for 3°



Diffuser material considerations

- Require:
  - Large MC scattering angle, i.e. short radiation length L_r
  - Small Nuclear interaction probability, i.e long nuclear collision length L_n (which includes elastic scattering)
- High-Z materials are much better (counter-intuitively)

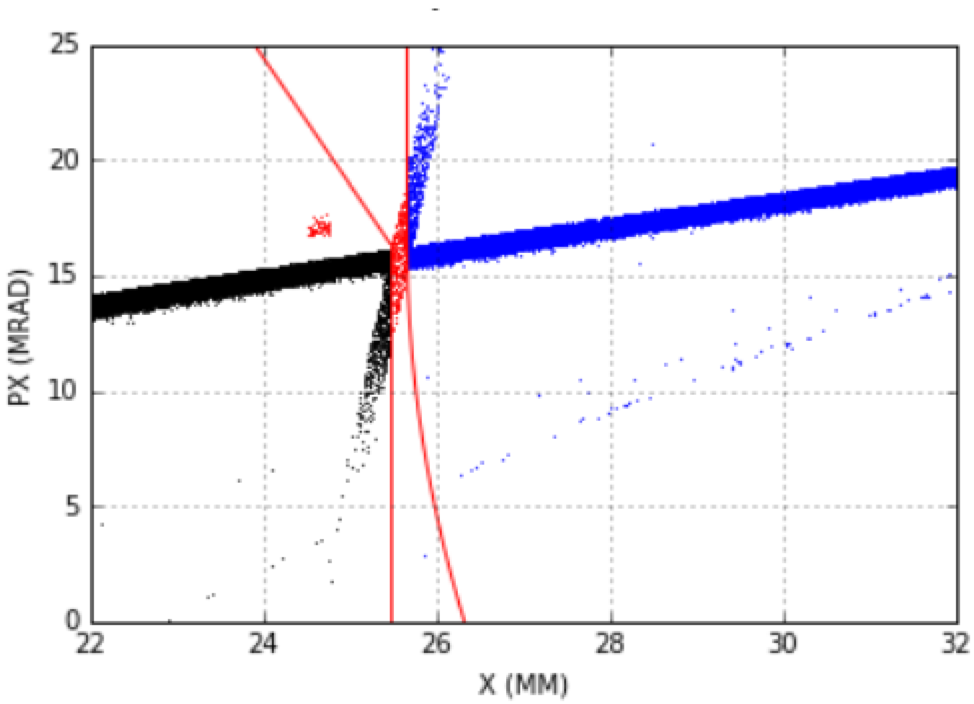
Parameter	$^{9}_{4}$**Be**	$^{12}_{6}$**C**	$^{28}_{14}$**Si**	$^{96}_{42}$**Mo**	WRe
ρ [g/cm^3]	1.8	2.0	2.3	10.2	19.7
λ_n total [cm]	29.9	29.6	30.2	9.1	5.6
λ_i inelastic [cm]	42.1	42.9	46.5	15.3	9.8
X_0 [cm]	35.3	21.4	9.4	0.96	0.35
Length [cm]	26	16	7.0	0.70	0.26
θ_e [μrad]	237	215	162	108	87
Inelastic loss [%]	46	31	14	4.5	2.6
Total loss [%]	56	40	19	6.4	3.7

Simulations

- Performed both in 2D and full 6D tracking of extraction process with home-brew python (fast, used for concept and sensitivity scans) and Mad-X (slow, used for validation and detailed quantification) routines, with scattering and loss routines (PyCollimate [8])
- ES with electric field, homogeneous average septum density, scaled according to assumed width
- ES angle optimised to minimise losses before any diffuser added

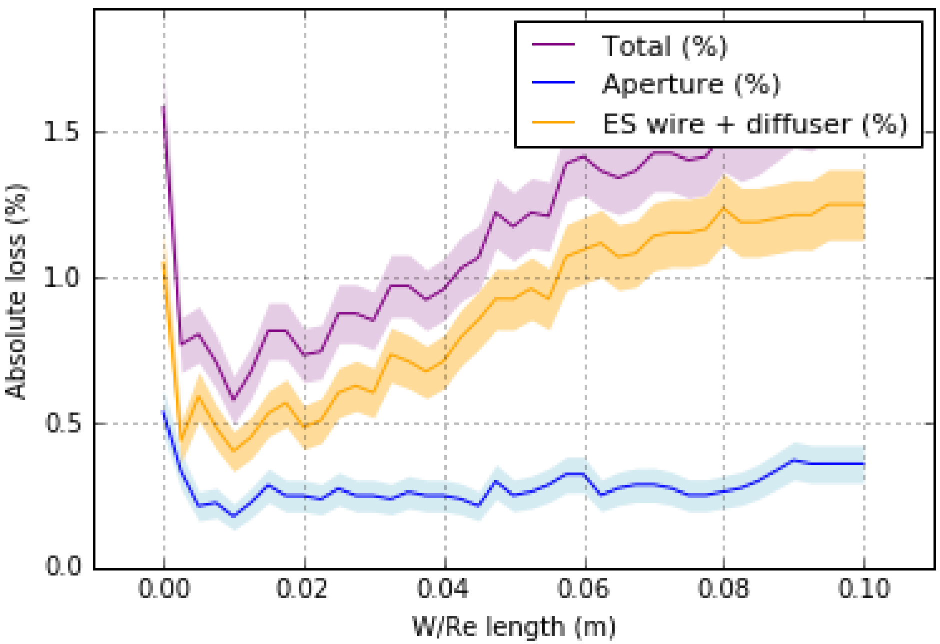
Simulations

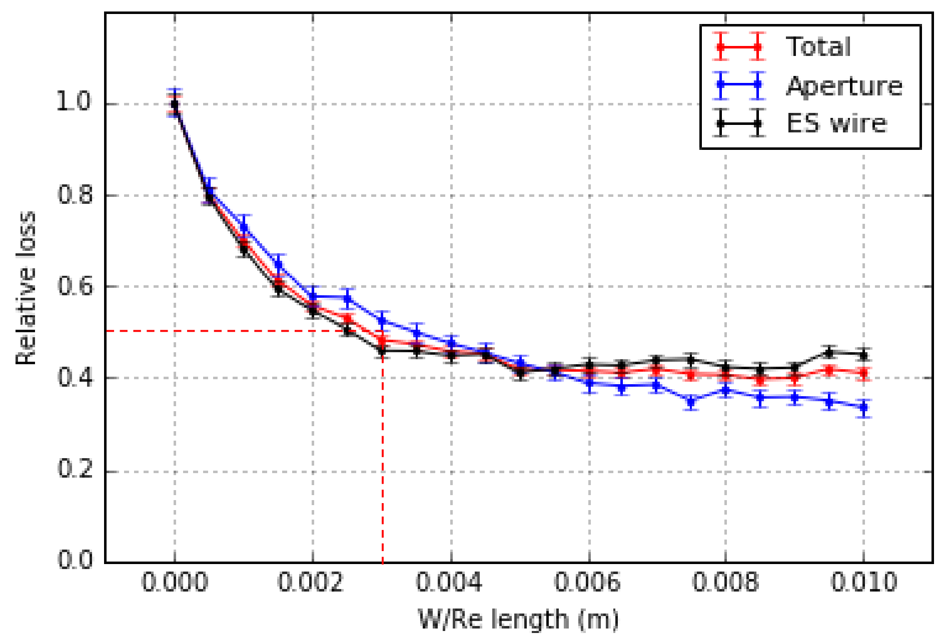
- Particle coordinates X,PX at ES, with diffuser



Results – diffuser length

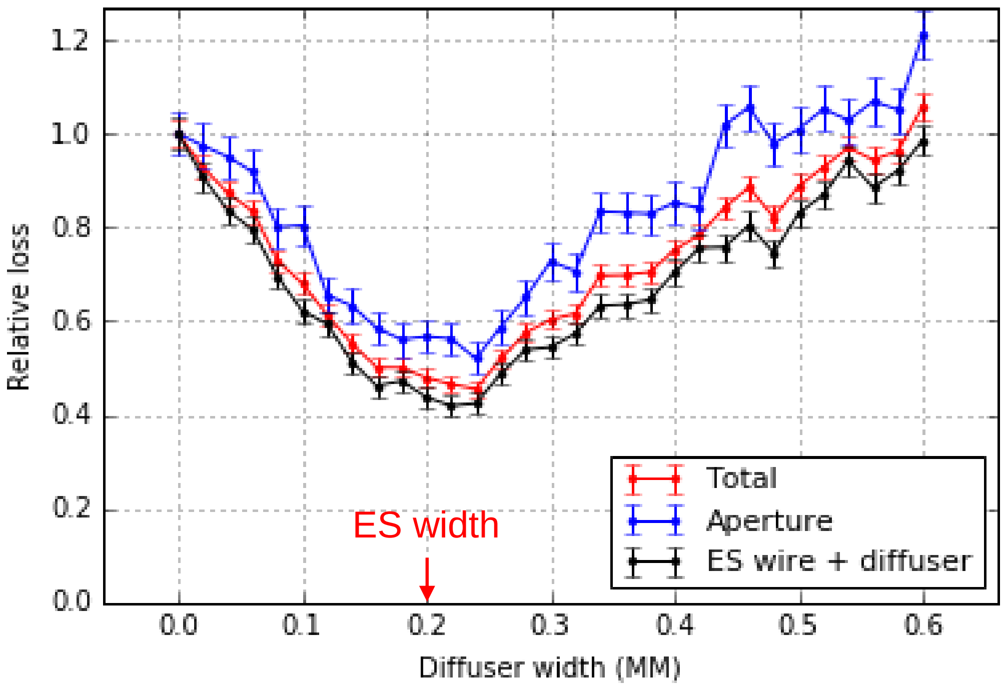
- For W/Re, length of 3 mm of material is enough to reach ~50% loss reduction (on ES wires and aperture)
  - Shallow minimum - keep length as short as possible





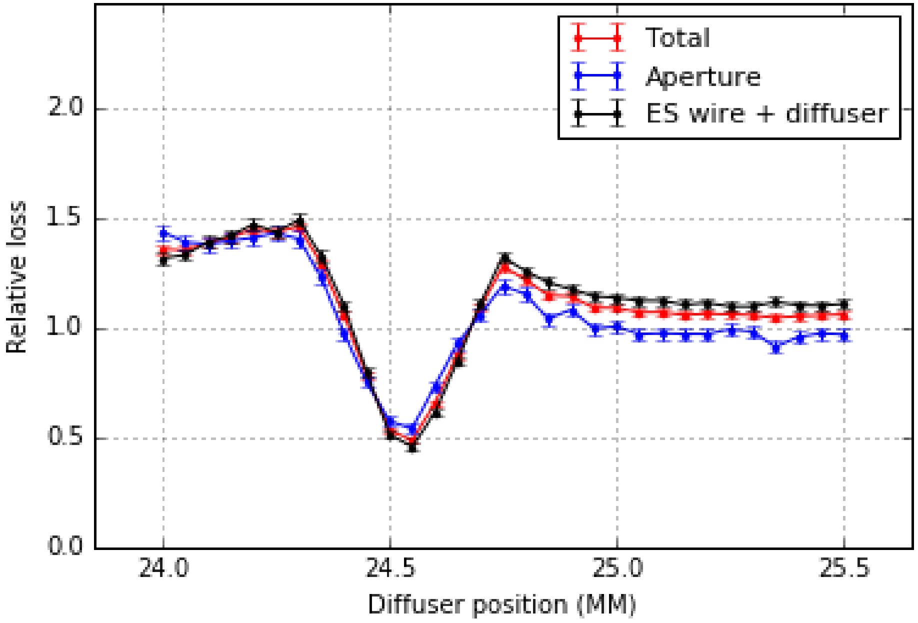
Results – diffuser width

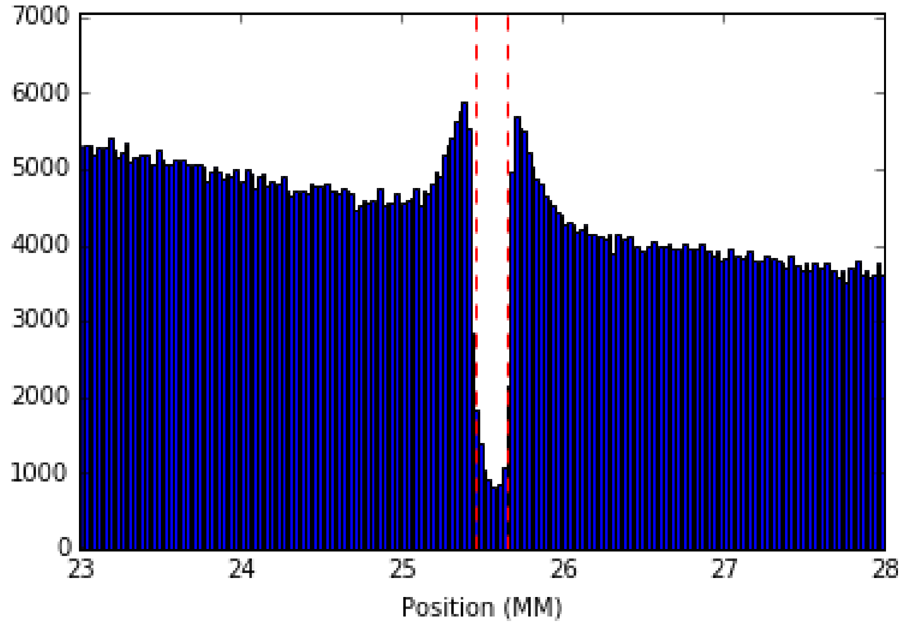
- Diffuser should be slightly wider than septum width
  - Assume 0.24 mm diffuser for 0.2 mm ES
  - ES width difficult to ascertain in reality – some ideas (see Matthew's talk), but more welcome - experiments?



Results – diffuser alignment

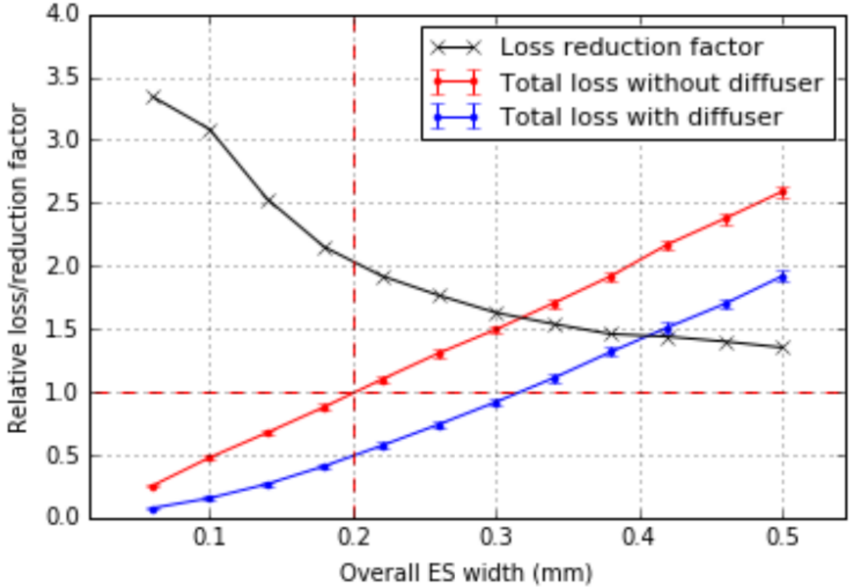
- Position alignment of diffuser fairly sensitive: ±50 um
  - 100 um error will seriously affect efficiency
  - 200 um error makes losses worse than nominal
- Can be mitigated (slightly) by wider diffuser…
  - But overall gain is then somewhat lower…





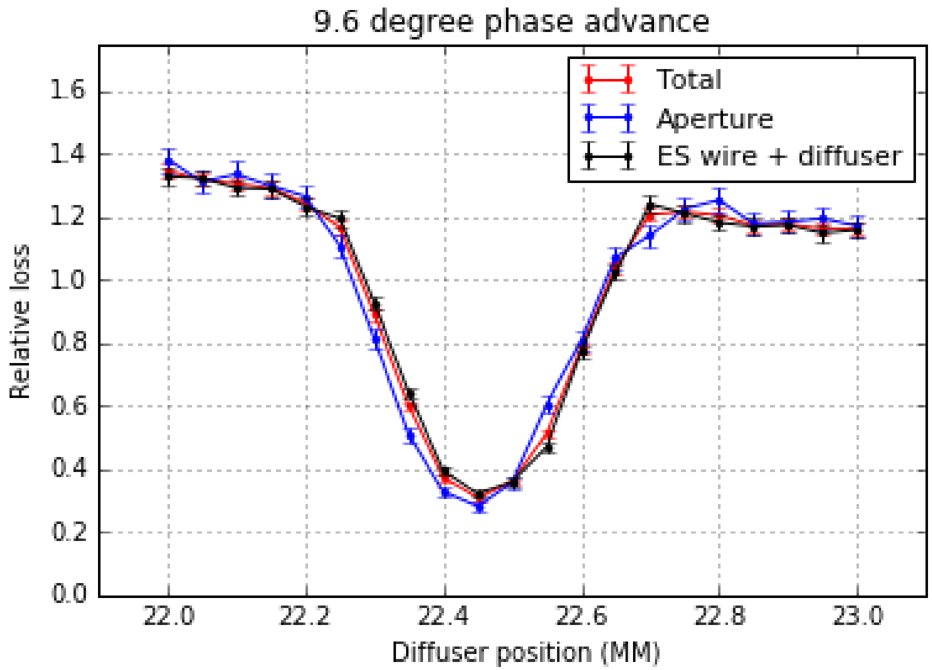
Result – ES width

- Relative gain in losses reduces for thicker ES
- Conversely, scope for improvement with better ES alignment/precision
- We need to accurately know the effective septum width!



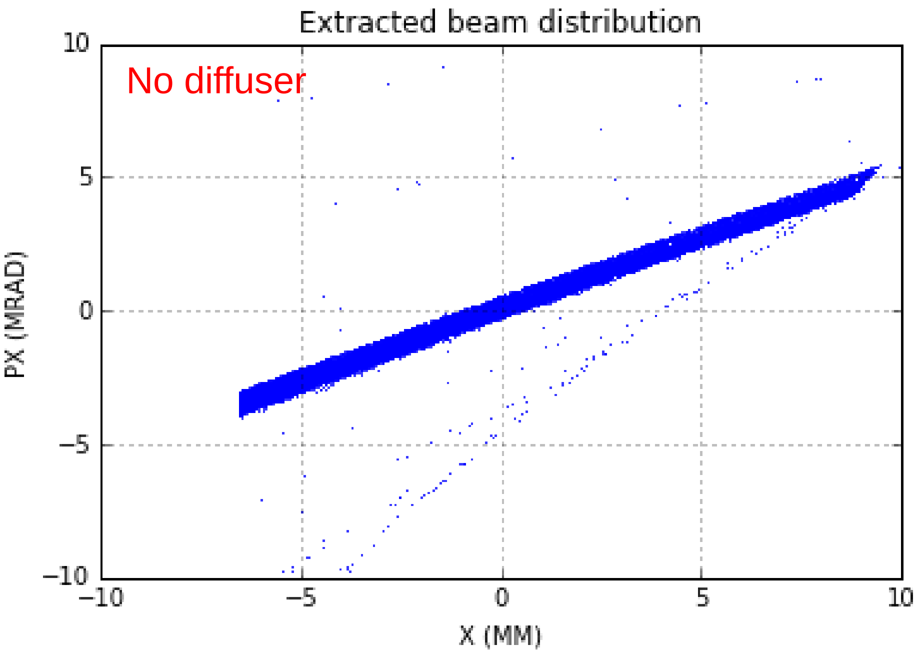
Results – better location?

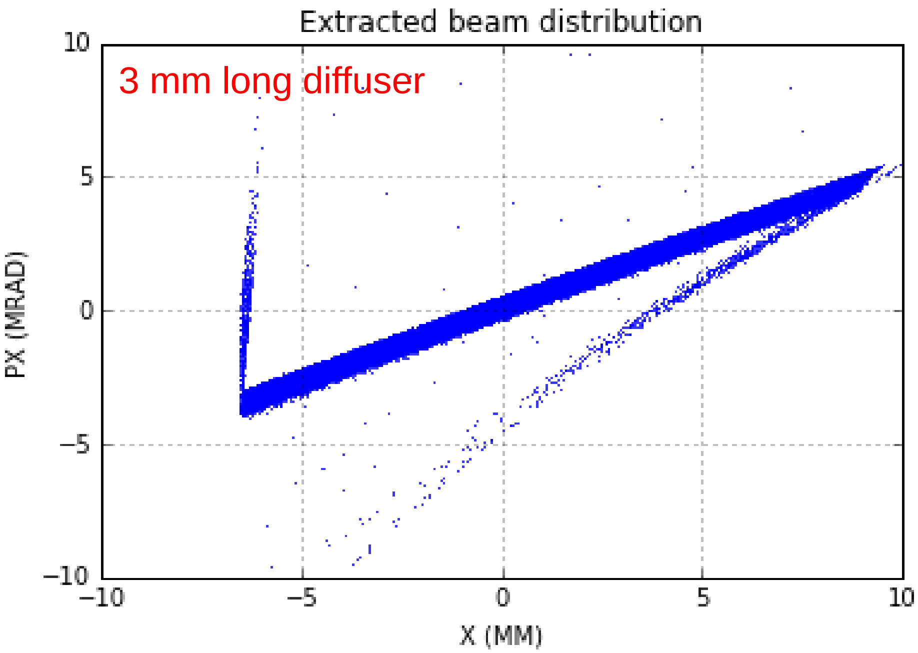
- Checked for (hypothetical) case with 6.4 and 9.6 deg phase advance
  - Get a factor ~2.8 and ~3.3 loss reduction respectively…
- No local SPS position available - would require a non-local option
  - To bear in mind for any new extraction design!



Results – halo & tails

- Degradation of extracted beam phase-space
  - No free lunch

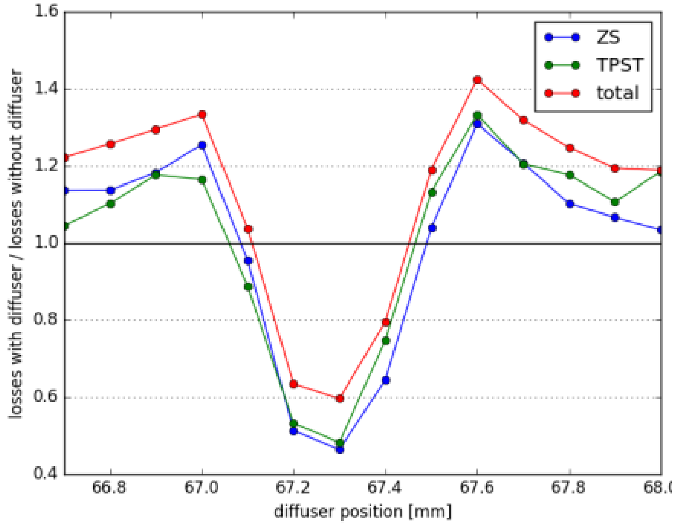




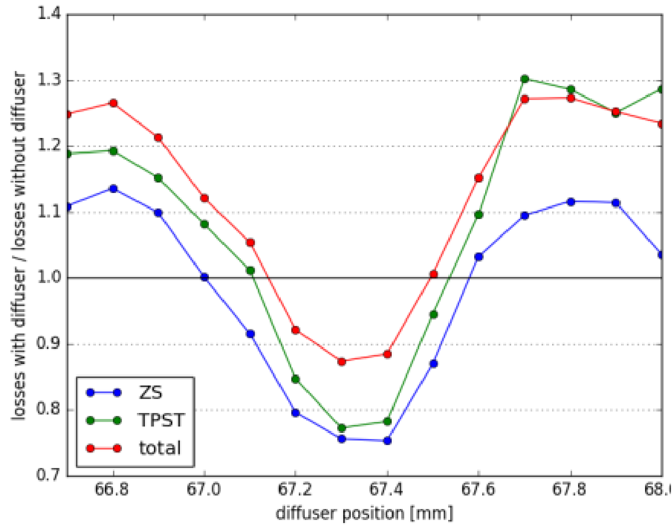
Results – madx + dynamic bump

- Full madx simulation agrees with simple version
  - Qualitative and quantitatively (note 0.3 mm diffuser)
- Dynamic bump essential (see Linda's talk)
  - 13% reduction without DB
  - 40% reduction with DB
- Effect should be easily measurable in both cases – good for 2018 tests

DB



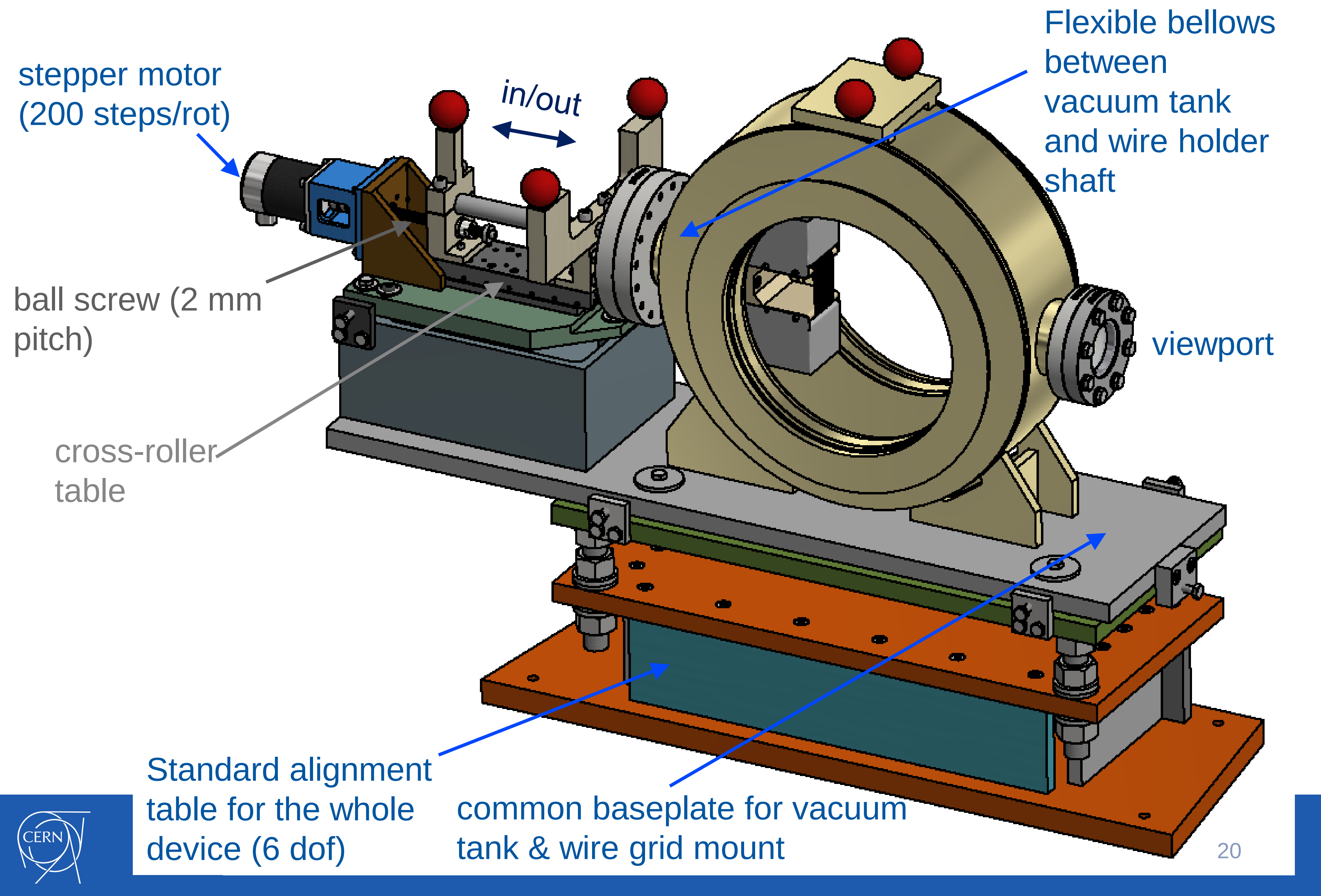
No DB



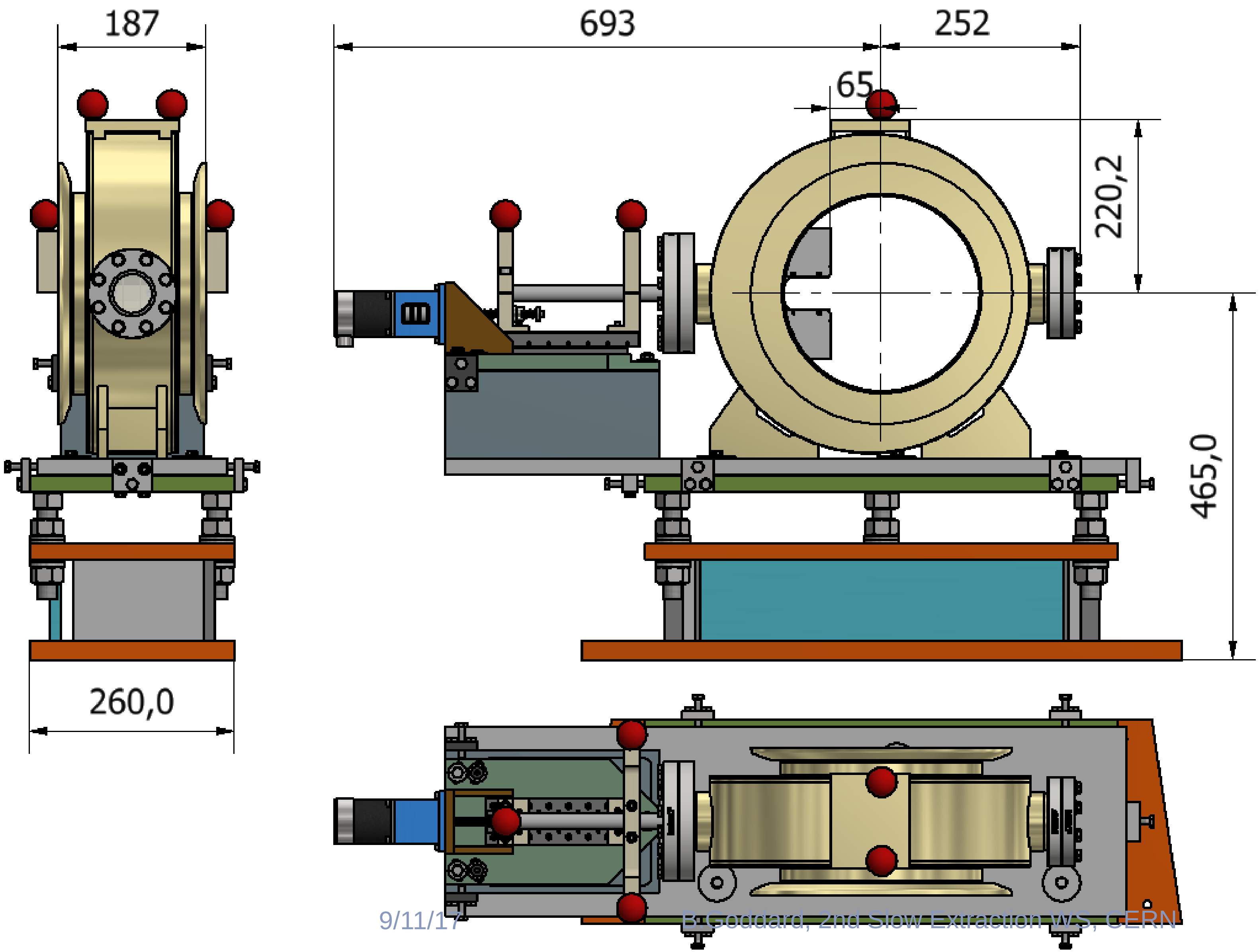
SPS prototype diffuser

- Installation before 2018 machine restart
  - Delivery: by 1st of December
- Collaboration between CERN and Wigner RCP (Budapest)
  - Design & project coordination: Wigner
  - Functional specification: CERN
  - Construction: Wigner + Engious Ltd (partner company)
  - Assembly: Wigner + Engious
  - Tests and installation: CERN

Concept and components

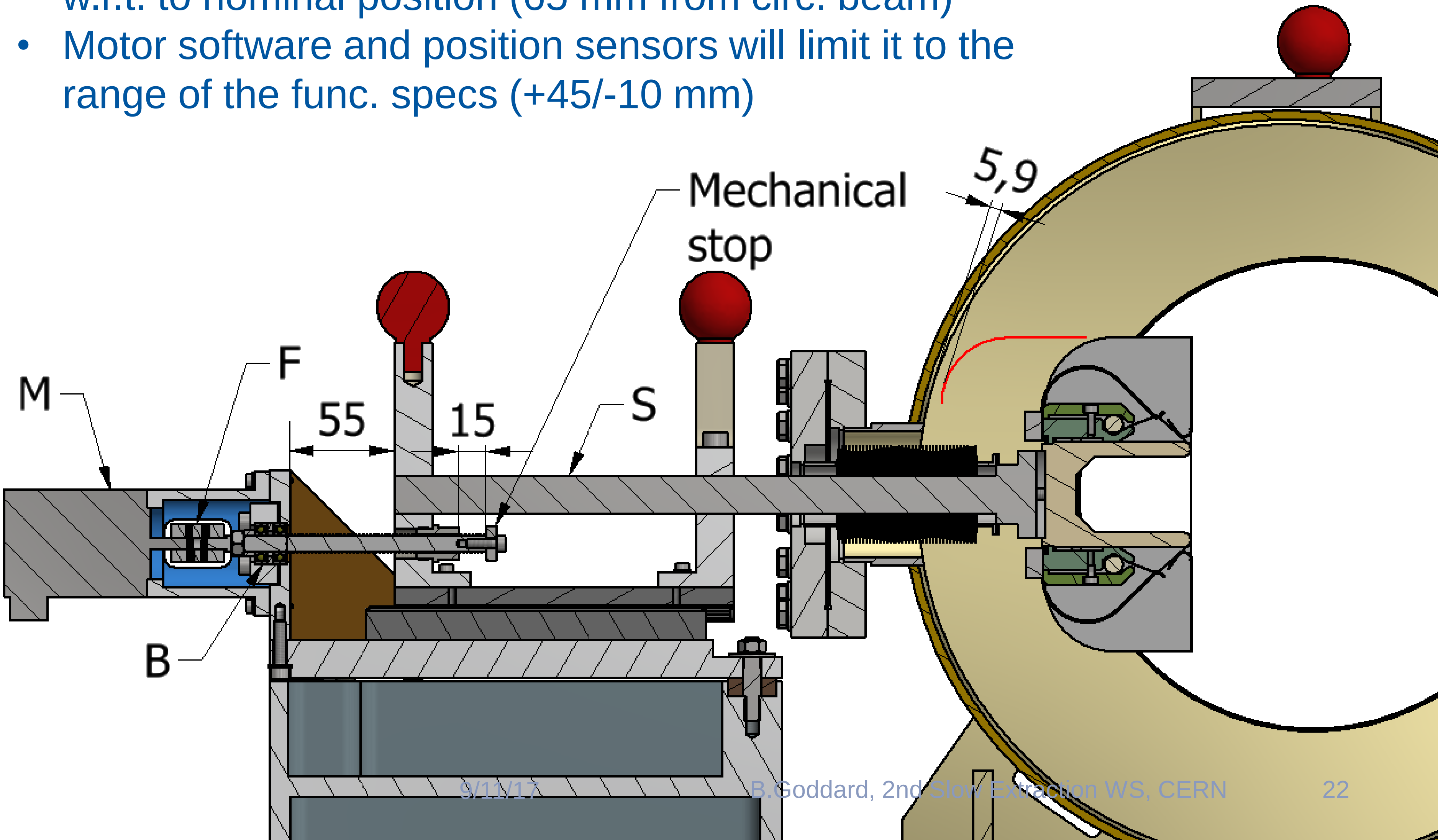


Space requirements (mm)

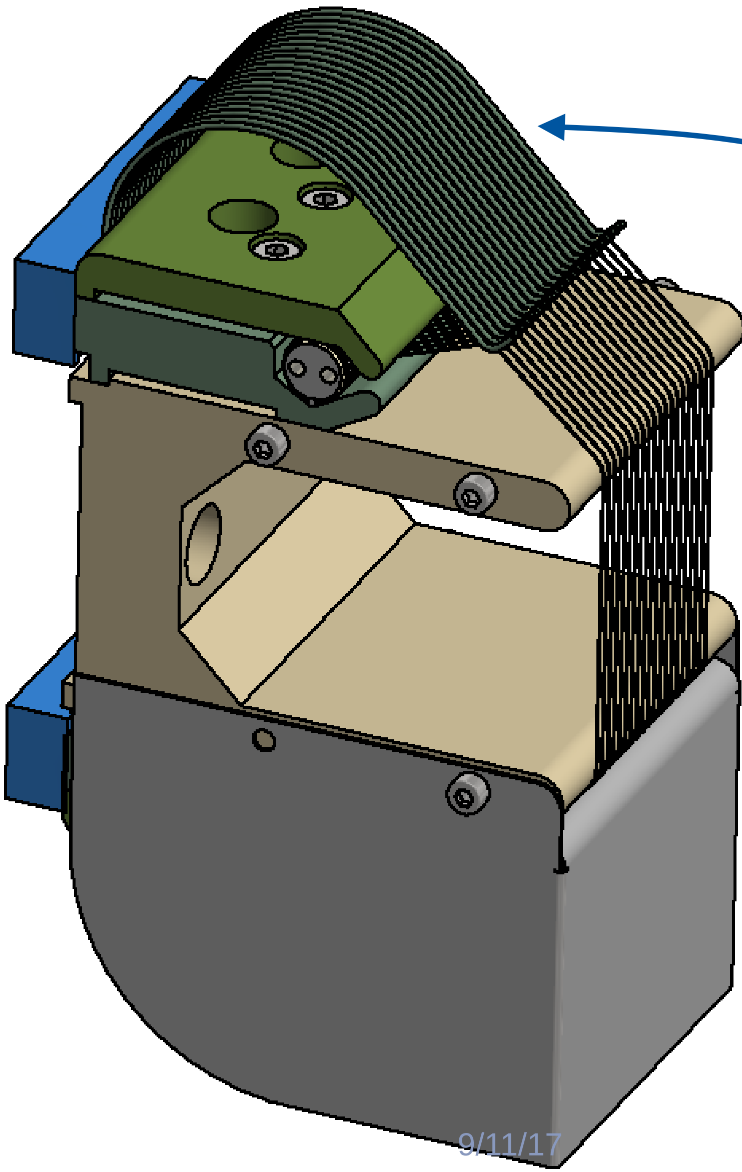


Movement range

- Movement is mechanically constrained to +55/-15 mm w.r.t. to nominal position (65 mm from circ. beam)
- Motor software and position sensors will limit it to the range of the func. specs (+45/-10 mm)



Wire grid assembly



Design borrowed from ZS but more compact

Fine springs tension the wires and pull them out if broken

Wire holder block is short, can be cut by wire very precisely

A cage bent from a sheet prevents the wires to fall back into the beam

Conclusions

- Diffuser should reduce losses on ES wires (and total loss)
- High Z material much better than low Z
- In SPS, location before QFA216 with 3.2° phase advance
- 0.3 mm wide x 3 mm long W/Re could give 40% loss reduction (relies on Dynamic Bump)
- Easy, low tech, insensitive to errors
- Alignment precision and stability needed: ±50 um
- Deploying prototype for 2018 tests…
- Further gains might be possible, dependent on
    - Precise knowledge of real ES width
    - Better phase location
    - Carbon ES wires

References

1. C. Germain et al., “Technical developments of the CERN electrostatic program”, 2nd Int. Symp. On Insulation of High Voltages in Vacuum, p.279 -291, Boston (1966).
2. M. Thivent, “Developpements liés à la construction des déflecteurs Electrostatiques:, PS/PSR/Note 83-8, 1983.
3. A. Durand, “ Efficacité d’un reseau de fils place devant la plaque du septum du Transfert continue à 12 GeV/c, Univ. de Rennes, FRANCE, 1974.
4. A. Durand, “Sur la Diffusion de protons de p=400 GeV/c par un reseau de fils place devant la plaue d’un septum electrostatique”, Univ. de Rennes, France, 1974.
5. V. Nagalsaev, “Requirements, Design and Challenge of slow extraction for the Mu2E experiment at Fermilab”, GSI Slow extraction workshop 1-3- June 2016, Darmstadt.
6. B.Goddard et al., “The Use of a Passive Scatterer for SPS Slow Extraction Beam Loss Reduction”, Proceedings IPAC 2017.
7. M. Tomizawa, “ Slow extraction at J-Parc”, GSI Slow extraction workshop 1-3- June 2016, Darmstadt.
8. F.M.Velotti et al., “SPS-to-LHC Transfer Lines Loss Map Generation Using PyCollimate”, Proceedings IPC 2015.

Simulations

- Simple tracking of X,PX with 6poles, ES, scattering routine and tune variation around 26.666
- ZS electric field used. ZS modelled as a single straight monolithic 17.35 m long object with fixed width (0.1-0.3 mm), and average density scaled accordingly
- 6pole strength, phase advance, emittance and tune scan adjusted to
  - 'extract' most of the beam in a reasonable time
  - produce representative separatrix (orientation, ΔPX and spiral step)
- No chromatic or feed-down effects (i.e. dynamic bump ON)
- Typically 2-5e5 macroparticles 'extracted', of which a few % are lost, statistical errors on losses of 1-2%
- Lose on SPS acceptance for particles scattered above certain amplitude
  - Only in H plane – will be vertical losses also from elastic scattering!
- ES angle optimised to minimise losses before any diffuser added

Simulations: scattering assumptions

- Take W/Re as material (well-known from ZS)
- Transiting length L of material, derived from X,X', length, width and septum E field
  - Material contained in 5x 2080 W/Re wires in ES spread evenly though the effective width of the ES
- Nuclear interaction:
  - Particles simply lost if undergoing inelastic nuclear scattering
    - Probability of loss is (1-exp(-L/Ln))
  - If not, scattered through (large) elastic scattering angle

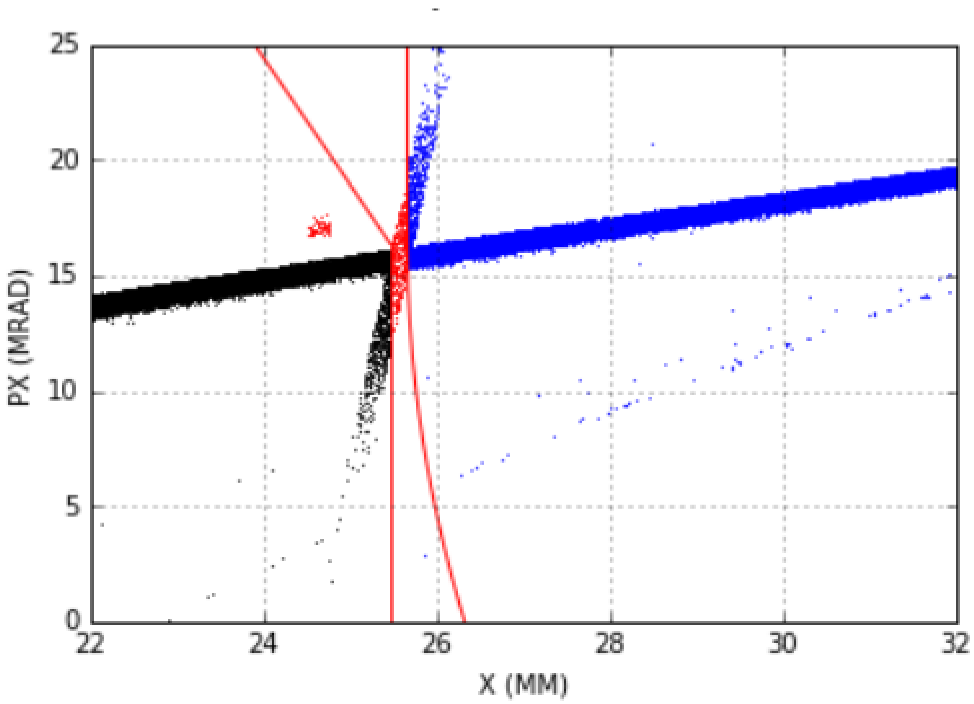
$$<\theta^2>_{x,y}^{1/2} = 197 \, / \, (A^{1/3} \, p(\mathrm{GeV}/c)) \ \mathrm{mrad}$$

- Surviving particles scattered through (smaller) random angle selected from Gaussian, with:

$$\theta_0 = \frac{14.1 \ \mathrm{MeV}}{pv} z \sqrt{\frac{L}{L_R}} \left[1 + \frac{1}{9} \log_{10}\left(\frac{L}{L_R}\right)\right] \qquad \mathrm{rad}$$

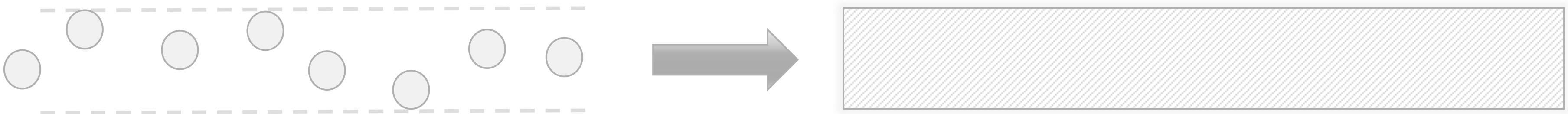
Simulations

- Particle coordinates X,PX at ES, with diffuser

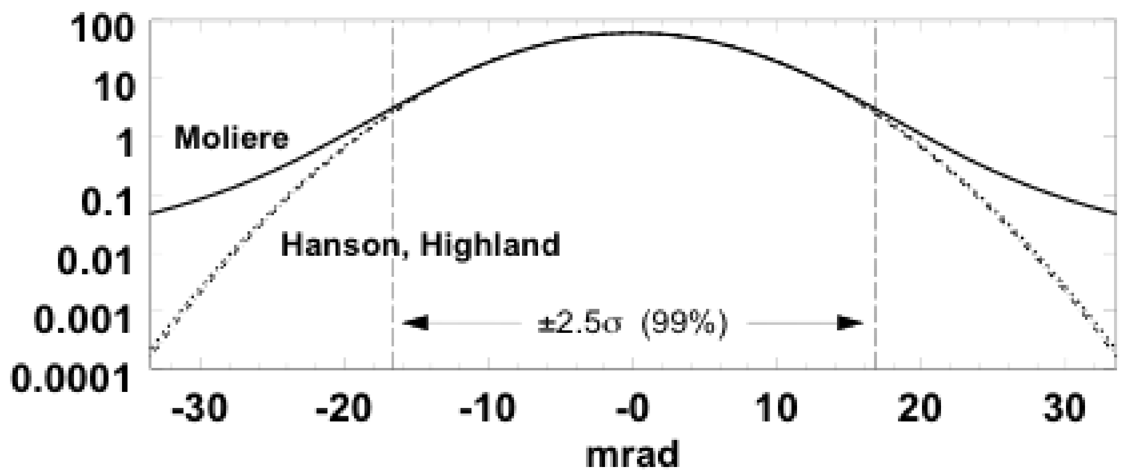


Comment on assumptions

- Could use a more detailed study of the effect of the ES wire misalignment
  - Present assumption very simplistic

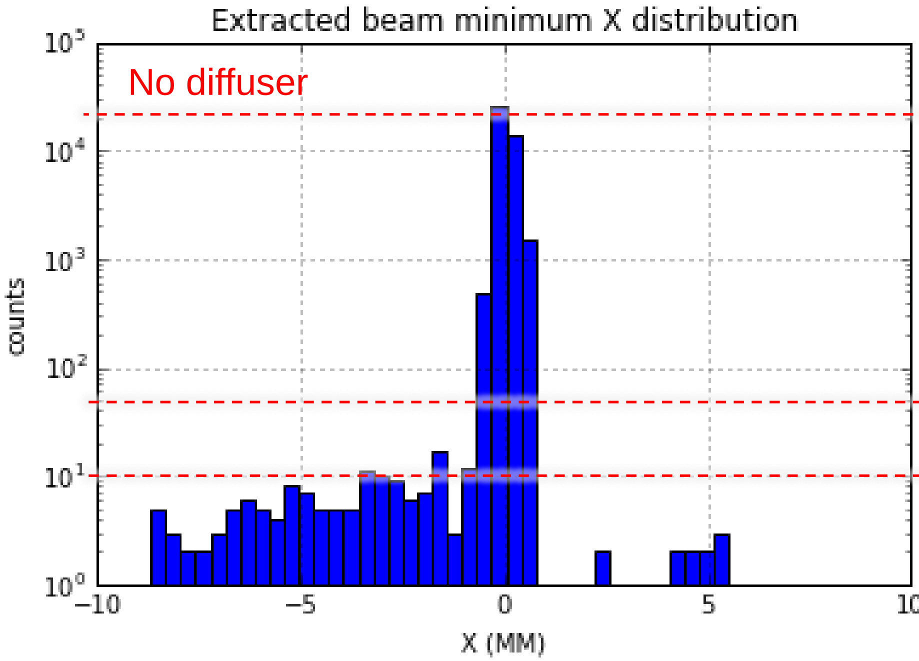


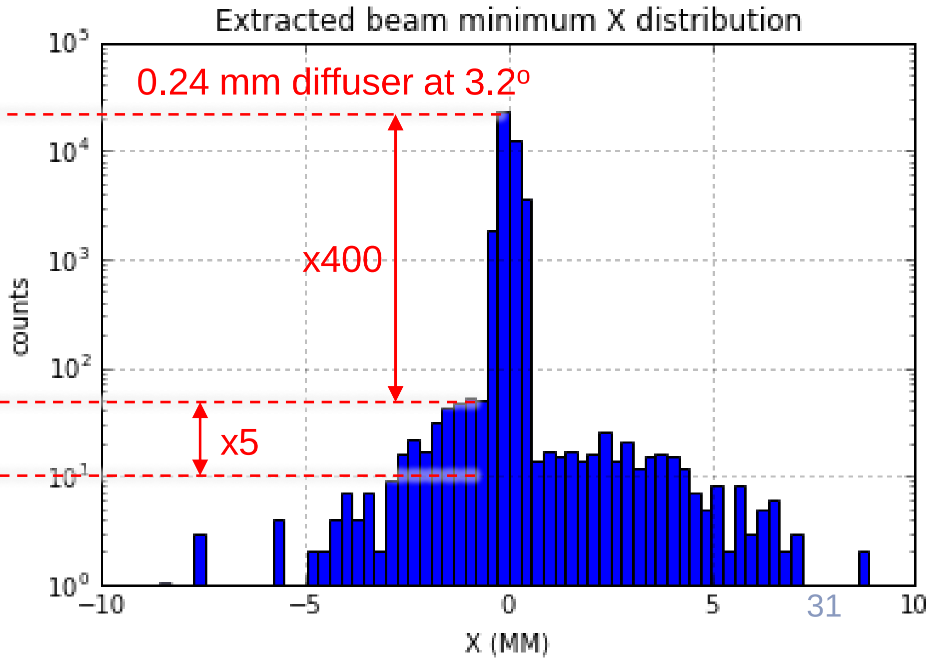
- Simple MC scattering following **Highland** (NIM 129 (1975) 497-499) fit of Molière/Bethe/Hanson theory
  - Under-estimates large angle scattering (above 2.5 σ) for 1%



Tails on extracted beam

- Yes, though emittance essentially not affected
  - Basically all the ‘saved’ losses go here
  - ~5x higher than without diffuser
  - Issue for splitter losses? Maybe not for SHiP…
  - Could consider collimation in TT20?



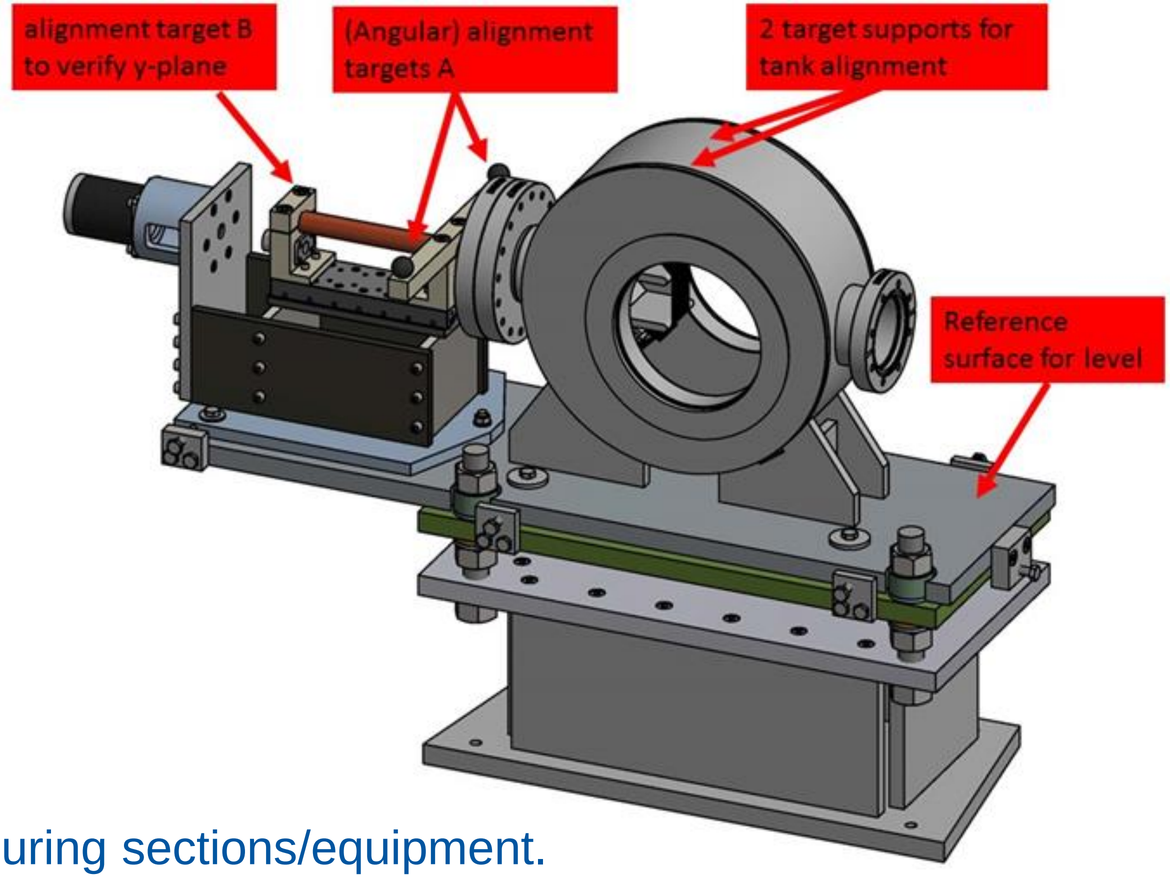


Different ES/diffuser combos

- Carbon ES with W/Re diffuser is better than W/Re for both

ES	Diffuser	Length	Loss	Factor
WRe	none	-	1.6%	-
WRe	WRe	3 mm	0.8%	2.0
WRe	WRe	30 mm	0.6%	2.5
WRe	Mo	20 mm	0.7%	2.3
WRe	C	100 mm	1.2%	1.3
C	none	-	1.2%	1.3
C	WRe	6 mm	0.5%	3.0
C	C	50 mm	1.0%	1.7

Alignment principle

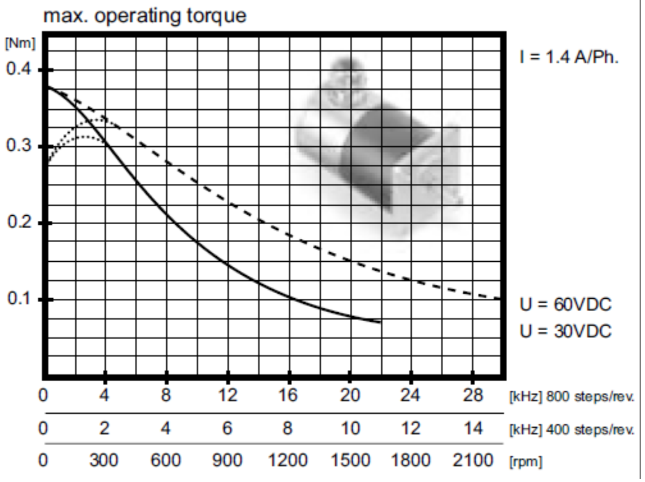


Support fixed on girder.
Tank aligned with neighbouring sections/equipment.
Displacement system of wire array adjusted separately to obtain alignment of wires w.r.t. the ZS anode.

Motorisation and electronics

- We'll use type Maccon SM56.1.18J1.Z303
- It comes with a LTN resolver attached
- The motor has been adapted to survive a TID of 10 MGy,.
- the mechanics should be designed to include a reference cam and limit switch, to allow automatic calibration.

Current per phase	Step angle	Holding torque	Detent torque
[A]	º	Nm	Nm
1 – 1.4	1.8	0.45	0.04



Will reuse and adapt electronics from HST (Linac 4) stripping foil installation.
Software to be modified.
Cabling required between BA2 and LSS2 (SPS tunnel).