Accelerator to target interface problems with high power beams

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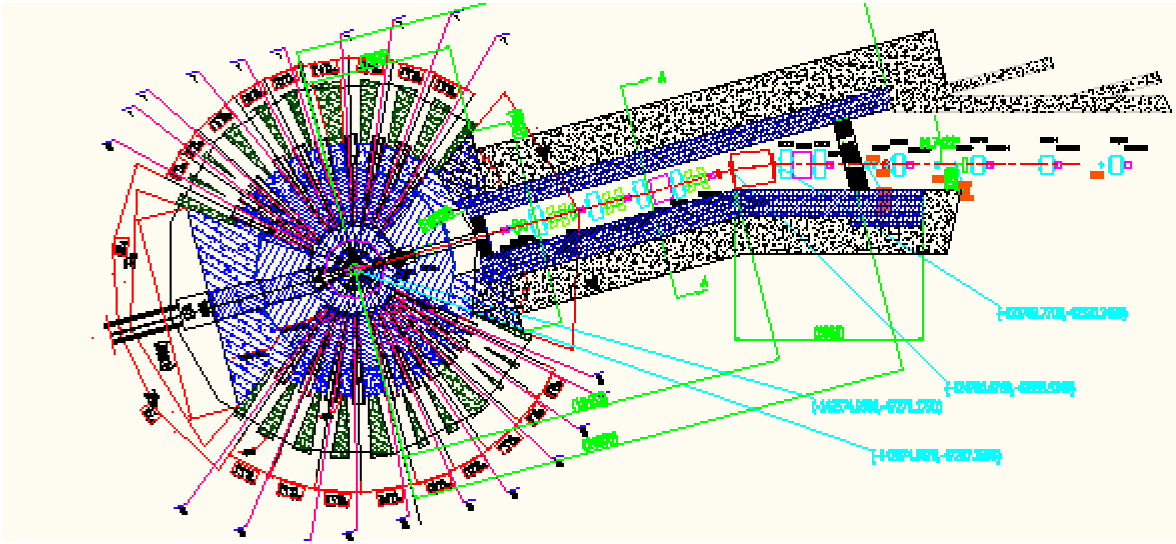
Topics

- Main interface problems with high-power beam on target
- Beam spot uniformization using nonlinear magnets
- Back-streaming neutrons and treatment
- Proton beam windows
- Beam monitoring in radiation-hard regions
- Summary

Main interface problems with high-power on target

- Uniform beam spot
  - To prolong lifetimes of target vessel and proton beam window (radiation damage); cooling;
- Back-streaming neutrons
  - Very high flux, damage to devices in the beam transport line; radiation shielding burden
- Proton beam windows
  - Lifetime due to irradiation, cooling problem, multiple scattering effect
- Beam monitoring
  - Monitoring beam centering and profile at target; lifetime and shielding of probes in a radiation-hard region

- Layout considerations
  - For spallation neutron sources: usually horizontal beam injection. The proton channel is within the target-instrument hall, heavy shielding wall is needed.
    - A bending magnet close to target is preferred to treat back-streaming neutrons, but not with the case of a muon target present (momentum spread too large).
  - For ADS: usually vertical beam injection, channel shielding compatible with the transmuter's maintenance also from the top.
    - A bending section exists naturally
- Maintenance problems: proton channel difficult to access after use, remote handling needed



CSNS RTBT-Target layout (left)

IFMIF HEBT-Target layout (lower)

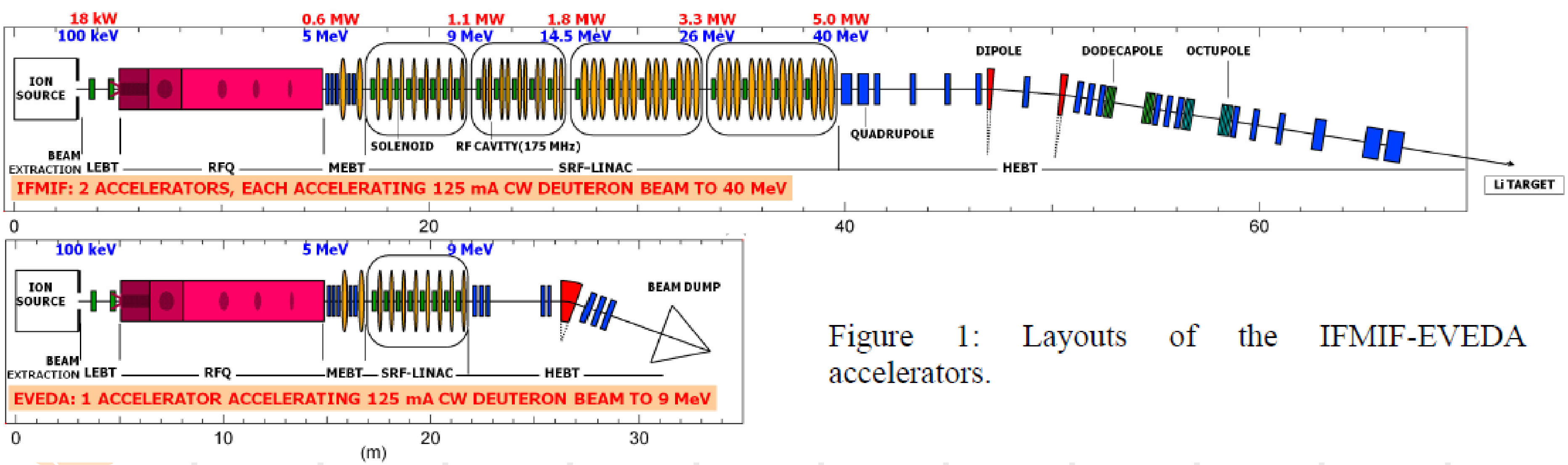
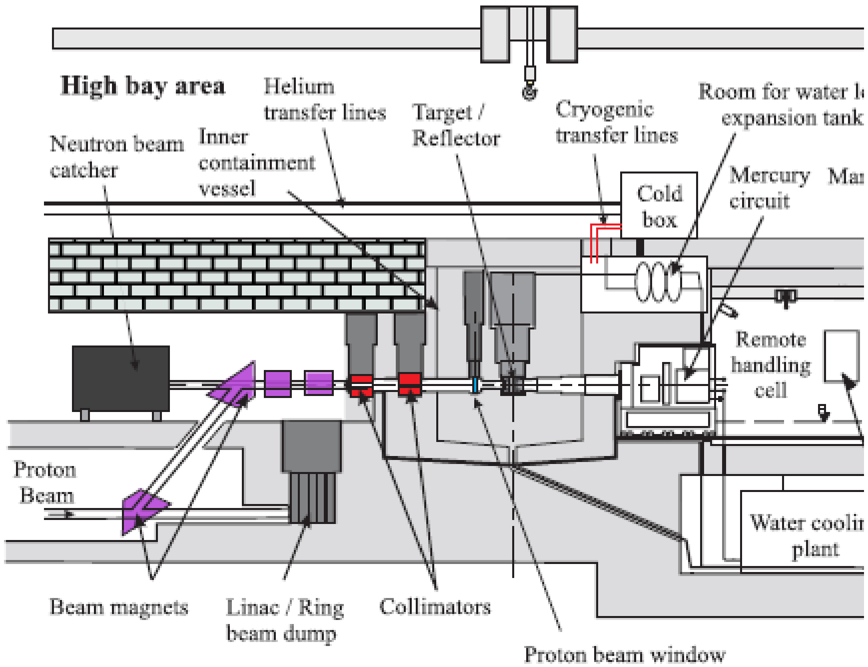
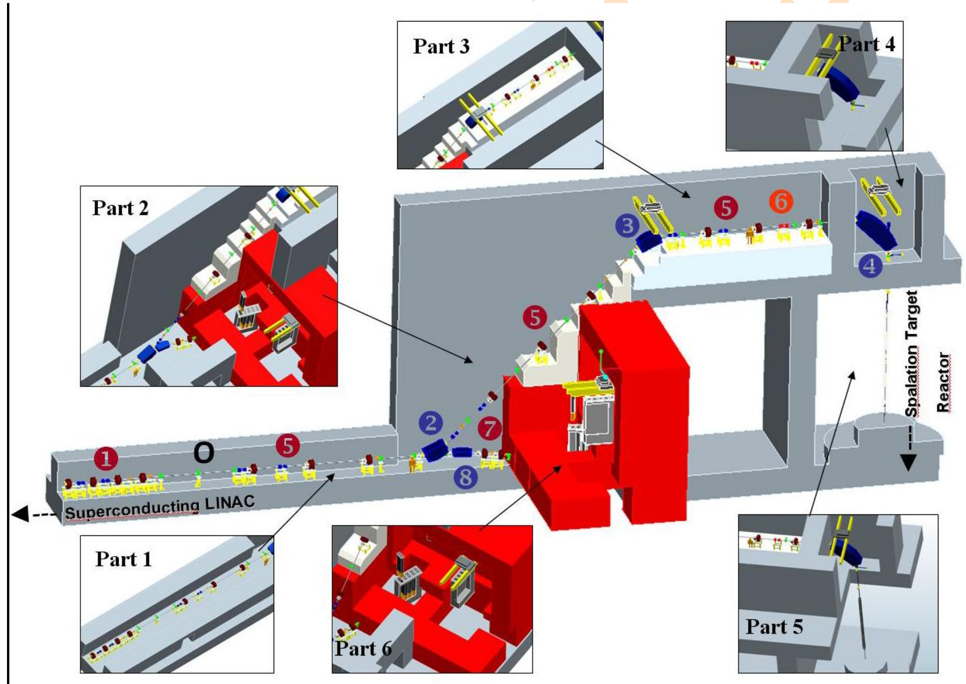
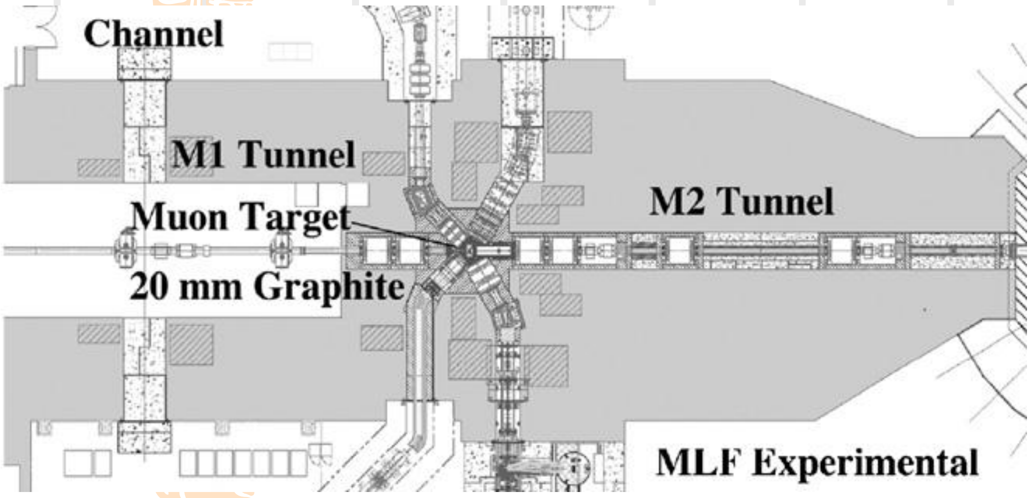


Figure 1: Layouts of the IFMIF-EVEDA accelerators.







Upper Left: ESS (2003 design)

Lower Left: J-PARC

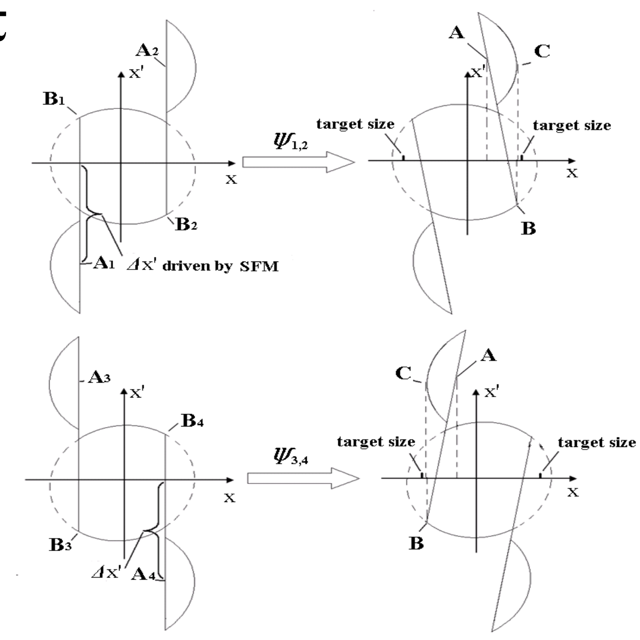
Upper Right: MYRRHA

Beam spot uniformization methods

- Time-dependent beam spot uniformization methods
  - By using scanning or wobbling magnets, sometimes combined with scattering foil to increase the uniformity
  - Suitable for CW or long-pulse beams, perhaps not very high beam power
  - Widely used in electron beam irradiation applications and hadron therapy
- Time-independent methods
  - By using nonlinear magnets or scattering foils
  - Suitable for both CW and pulsed beams, scattering foils can be used only for low-intensity beams (proton therapy)

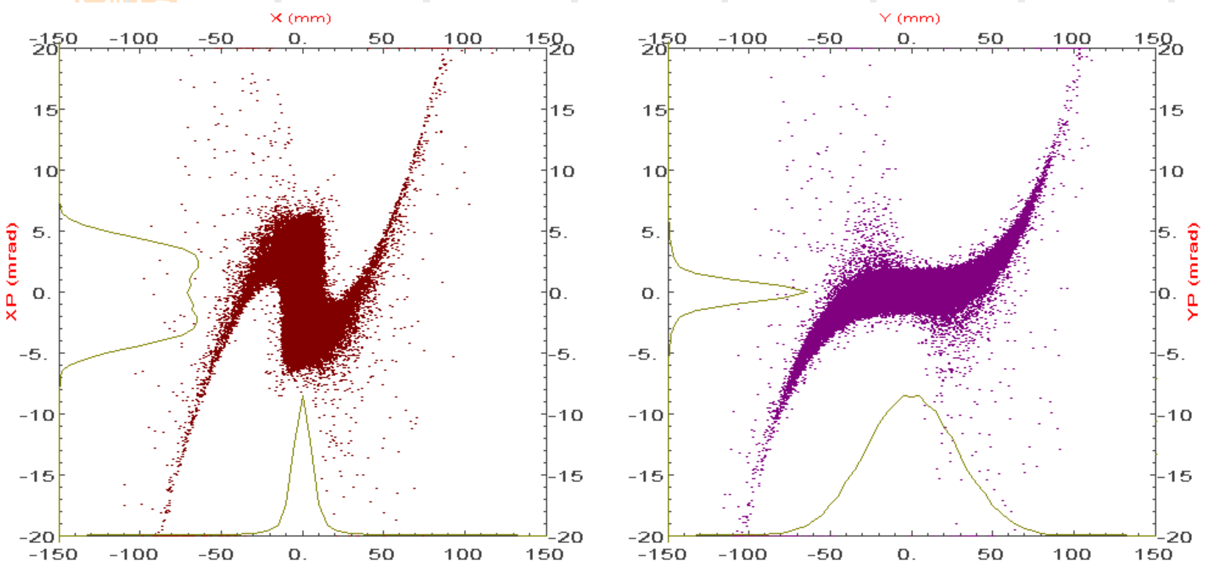
Spot uniformization for high power beams

- For pulsed beams, only nonlinear magnets can be used
  - Folding halo particles onto beam core
  - Flat beam profiles at nonlinear magnets to decouple the two transverse phase planes
  - Phase advances between the non-linear magnets and the target should be close to $\pm\pi$ or $\pm 2\pi$



$$\begin{cases} n\pi - \left[\arcsin\frac{1}{r} + \arcsin\left(\frac{5}{6r}-1\right)\right] \le \psi \le n\pi - \arcsin\left[\left(1-\frac{1}{r}\right)\frac{\varepsilon_x}{\sigma_{Sx}}\frac{B\rho}{B_s L_s}\right] \\ n\pi + \arcsin\left[\left(1-\frac{1}{r}\right)\frac{\varepsilon_x}{\sigma_{Sx}}\frac{B\rho}{B_s L_s}\right] \le \psi \le n\pi + \arcsin\frac{1}{r} + \arcsin\left(\frac{5}{6r}-1\right) \end{cases}, n = 0,1,2..$$

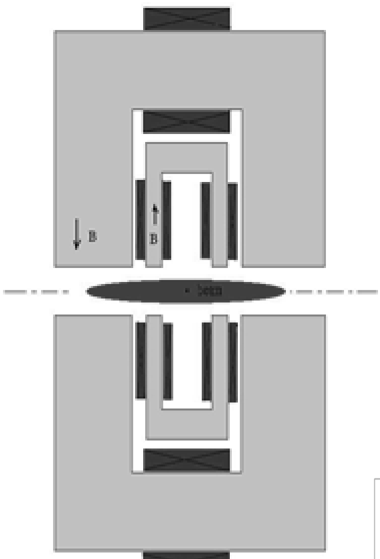
- More conventional: single octupole or a pair of octupole and dodecapole for each plane (horizontal or vertical)
  - Single octupole: simpler, but difficult to balance beam core and halo, may have larger beam losses
  - Pair of octupole and dodecapole: can make balance between beam core and halo, difficult to fabricate large-aperture dodecapoles
  - Not good for producing waists to place collimators

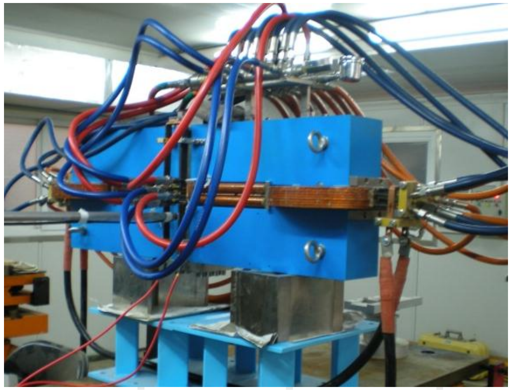


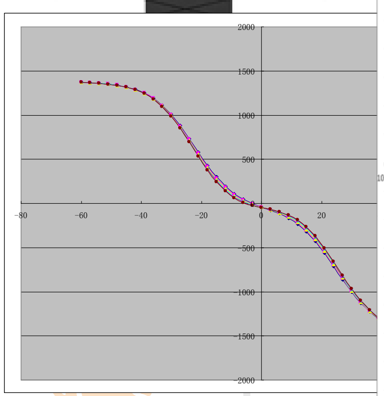
Single octupole:

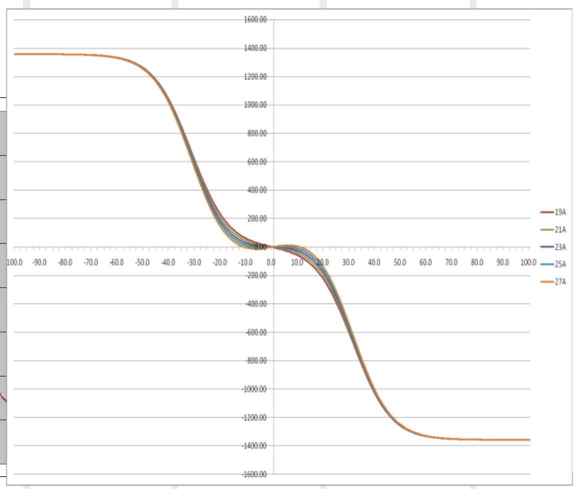
Distribution at second set octupole

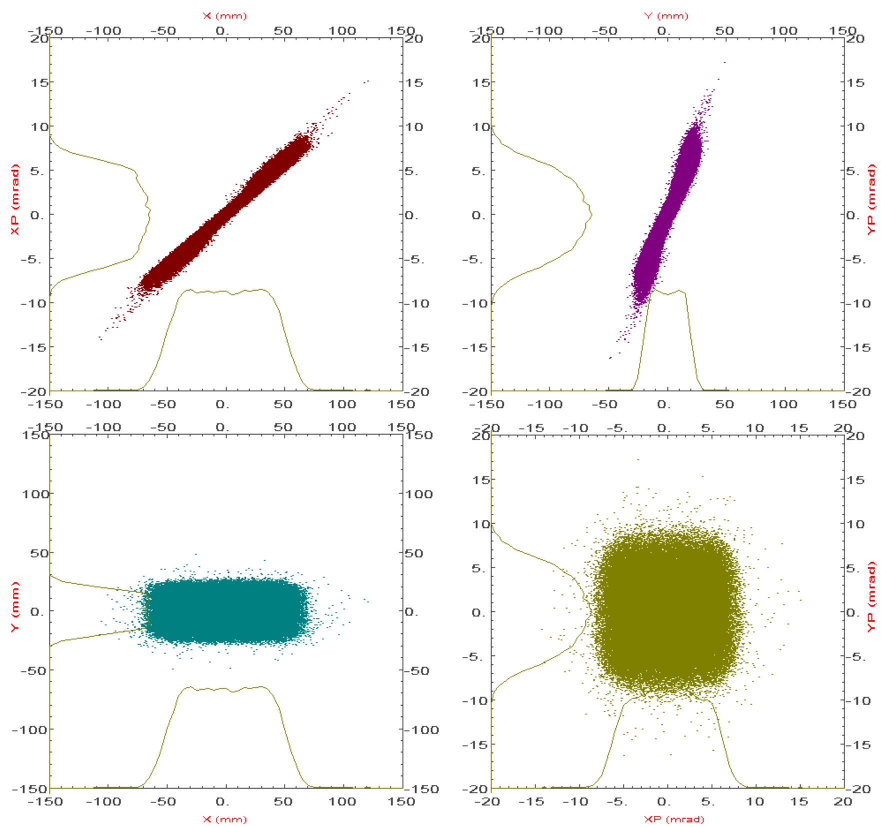
- Step-like field magnets: a pair of SFMs has similar performance to the OCTU-DODECA, but easier to adapt irregular distributions (e.g. something like dual-Gaussian); much cheaper; narrow magnet gaps (merit or demerit?)
  - Cut and past in the phase space



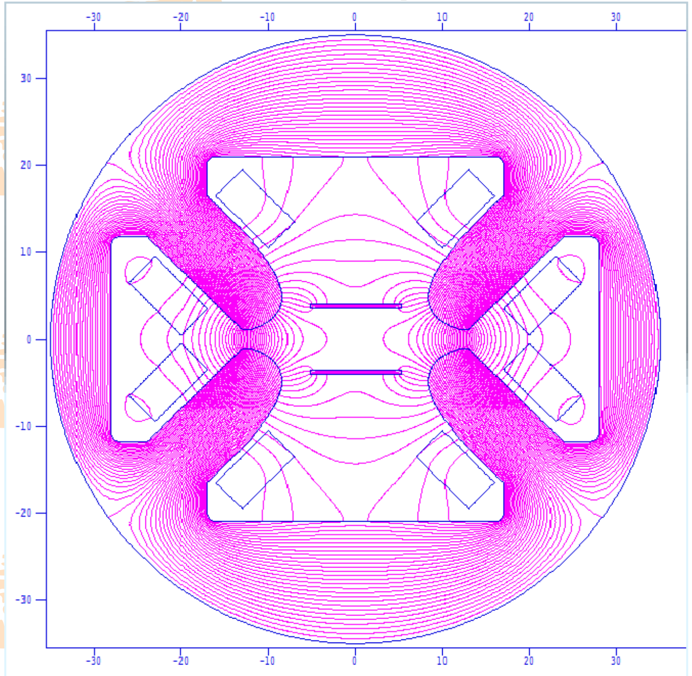


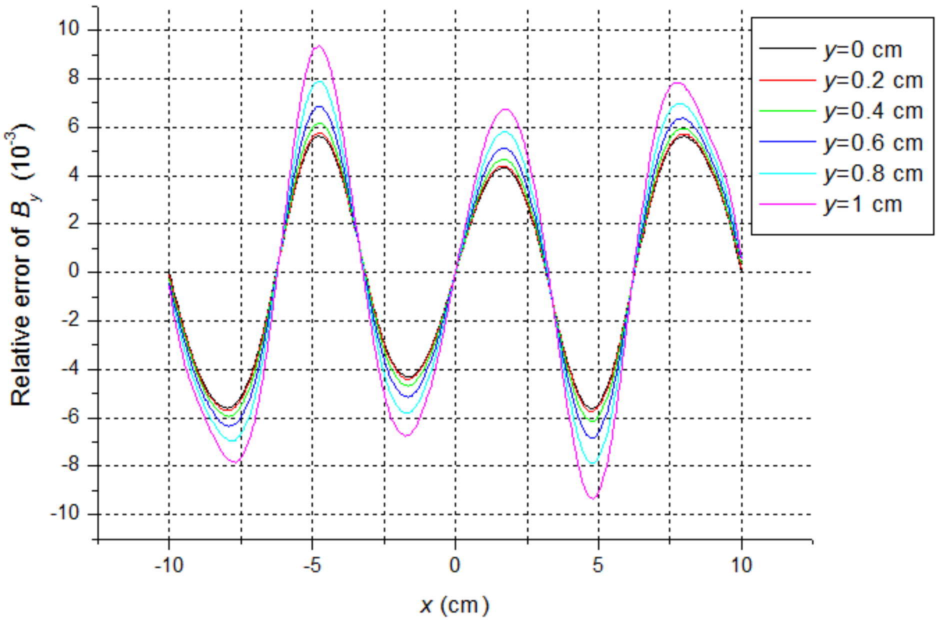


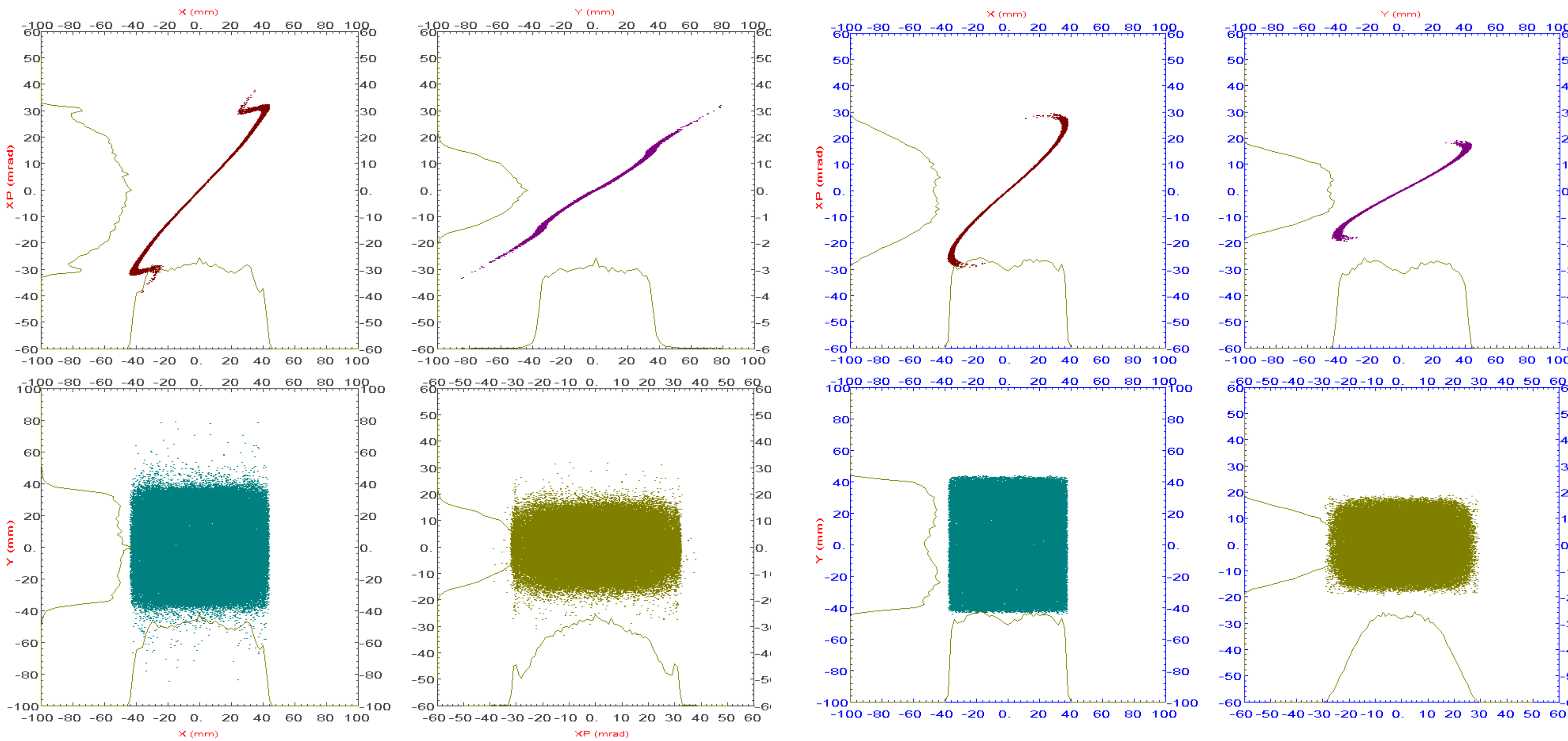




- Simplified multipole magnets: a new idea; different combinations of anti-symmetric 2nd, 3rd, 4th and 5th -order field magnets, recently proposed at IHEP
  - Special structure allowing any-order anti-symmetric multipole magnets
  - Compared with OCTU-DODECA combination, SEXTU-DECA combination looks to be better in performance and cheaper in cost



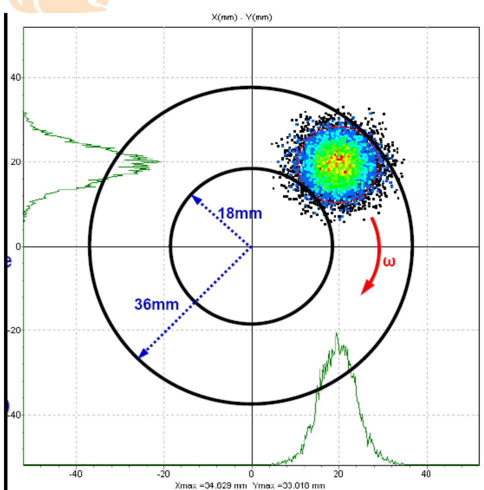


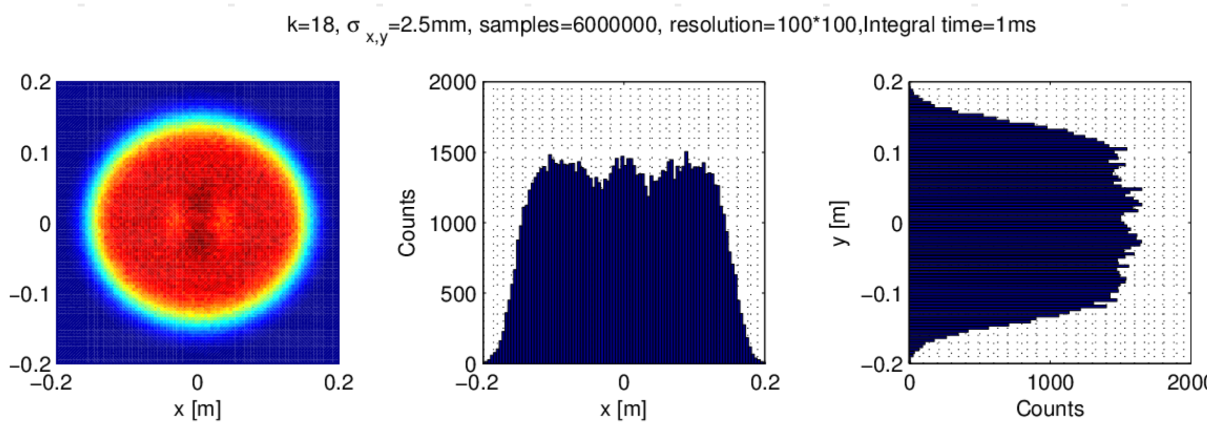


Simulation results at ADS RFQ beam test line:

Left: step-like field magnets;   Right: simplified 2nd order and 4rd order magnets

- For CW beams (ADS application), it might be possible to use wobbling or scanning magnets
  - A round beam spot is needed (actual target/transmuter design), which is difficult to obtain with non-linear magnets➔ more effort is needed
  - MYRRHA: raster scanning in hundreds Hz in X-Y
  - China-ADS: amplitude-modulated rotating dipole field in kHz (technically difficult)
  - It is difficult to produce uniform beam spot in neutron generation time of about 1 ms

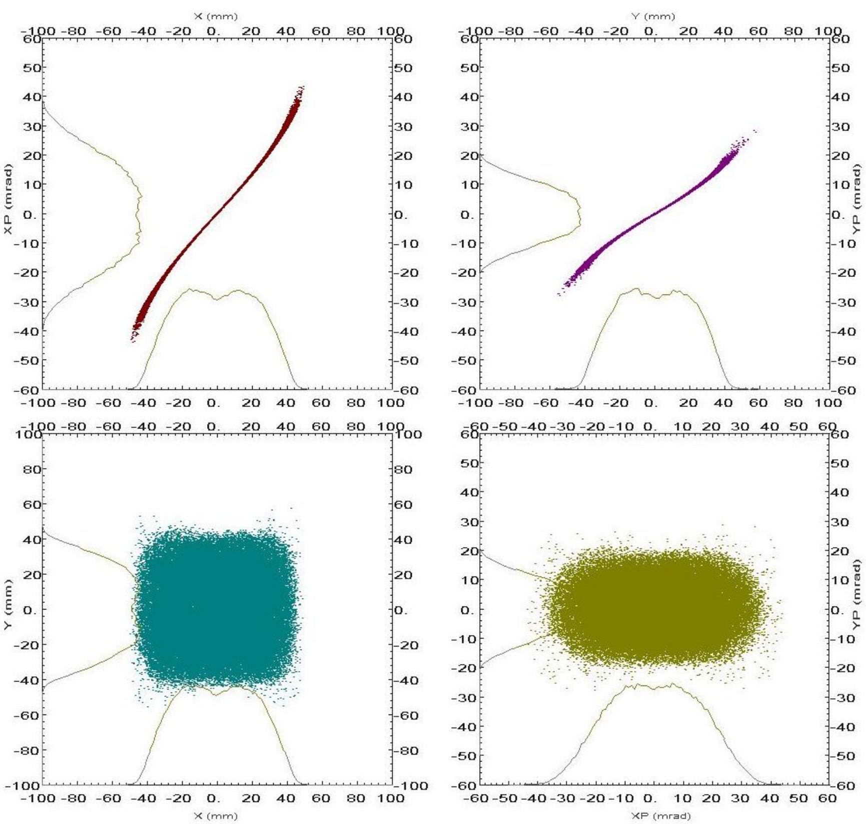


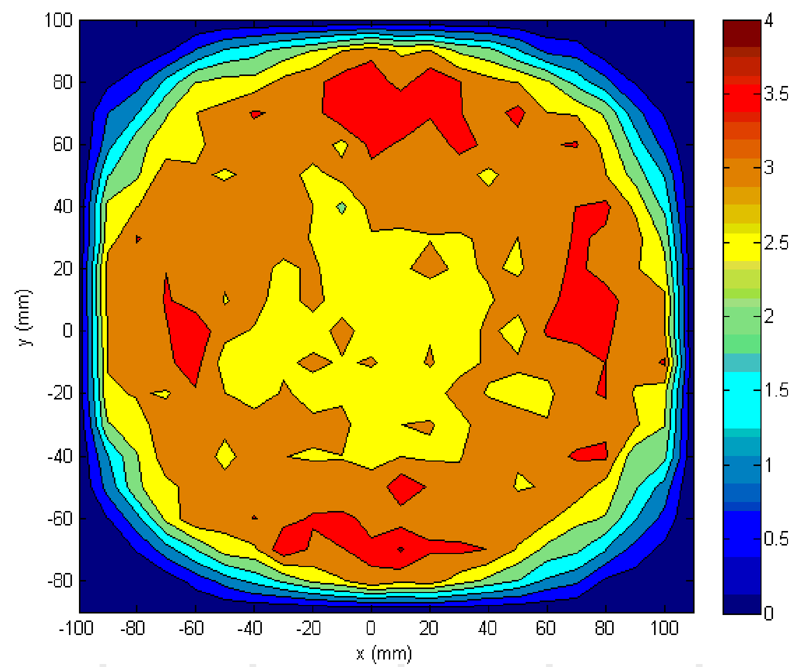


- My preference
  - Pulsed linac beam: step-like field magnets→ simplified SEXTU+DECA→ standard OCTU+DODECA
    - For a large beam spot or across an achromatic bending section, SFM preferred
    - For a relatively small beam spot or lower beam energy, simplified SEXTU+DECA preferred
  - Ring beam with sparse halo or dual-Gaussian: SFM preferred
  - CW linac beam: more effort still needed to meet the ADS requirement, e.g. producing round beam spot by coupling X-Y intentionally. (different methods are under study)

- A test result using two pairs of simplified SEXTU+ OCTU magnets: corner rounded (intentionally induced coupling)

(IHEP 3.5 MeV RFQ beam, by Zheng Yang)



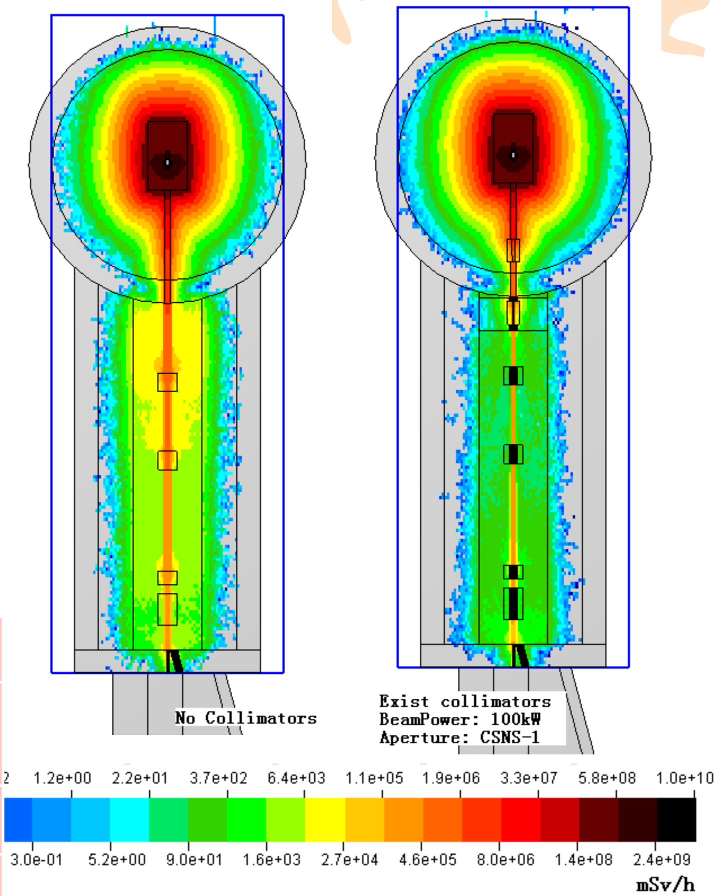


Another example by SFM

Back-streaming neutrons

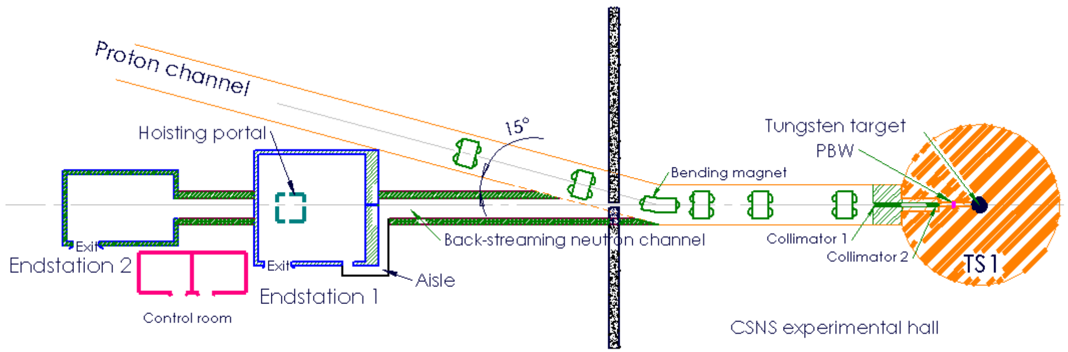
- Back-streaming neutrons along the incoming proton channel are very intense, very harmful to the devices in the proton beam line and also makes the shielding of the channel more complicated.
  - As an example, 0.5 MW beam @CSNS producing a dose rate of about 90 Gy/h at 9 m from the target without collimation, corresponding to a lifetime of 4.7 years for epoxy coils.
  - Magnets, beam diagnostics, vacuum devices, cables etc.

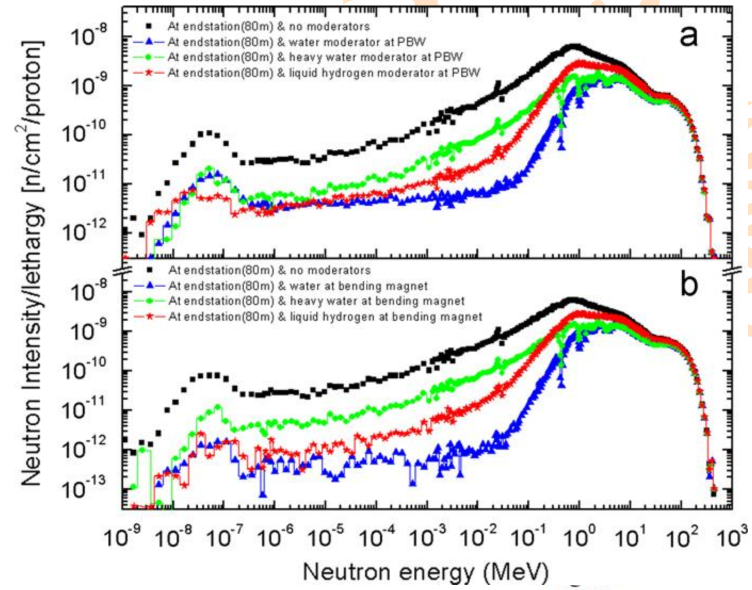
- It is important to have near-target collimators. A neutron stopper after a bending magnet is also recommended.
  - Collimators at proton beam waists are very efficient in shielding back-neutrons.
  - A dipole followed by a neutron stopper can localize back neutrons



Distance (Magnet)	Dose (W Coll)	Dose (W/ Coll)	Dose Ratio
	[mSv/h, @20cm]	[mSv/h, @20cm]	
8.9 m (Q30D)	598.6	963648	1610
12.3 m (Q29D)	790.8	450360	569
17.6 m (Q28A)	10614.8	270677	26
18.4 m (RT_BH)	9984.7	105362	11

- CSNS exploits back neutrons as White Neutron Source (about 47% neutrons >1 MeV)





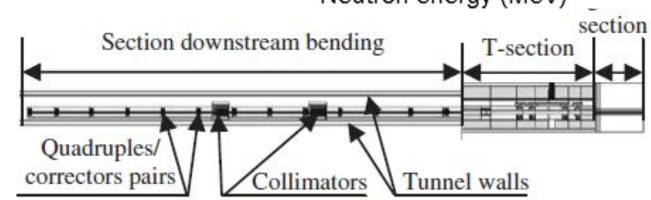


Fig. 4. Model of SNS RTBT portion, elevation view.

- SNS uses more sophisticated shielding design (no collimators close to target and no neutron stopper)

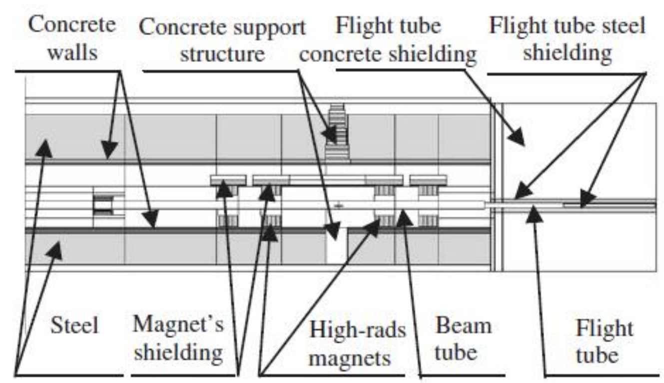
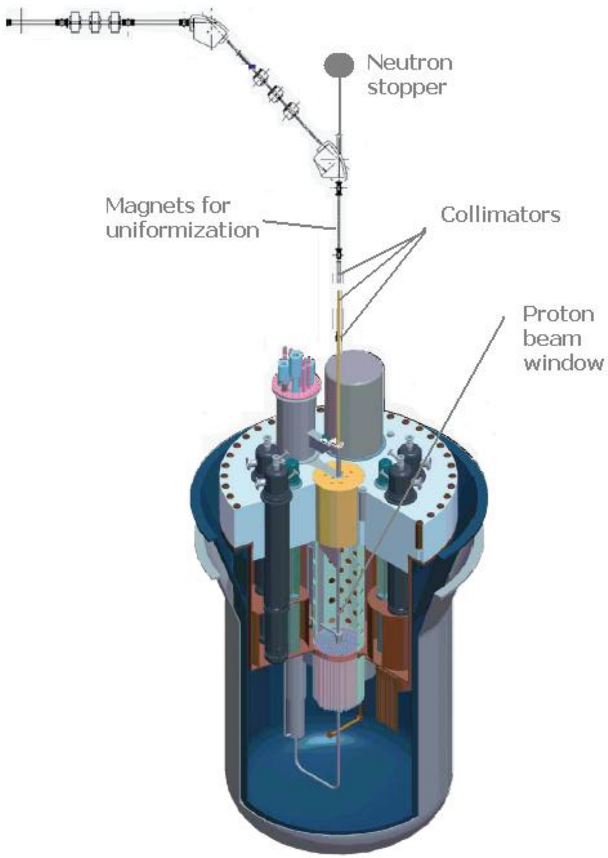


Fig. 5. Model of SNS RTBT T-section and flight tube section, elevation view.

- C-ADS back neutrons: very critical
  - Large proton beam power (15 MW), large beam spot (>ϕ200 mm)
  - Direction: sky (problem for environment)
- Preliminary considerations
  - Collimators at waists
  - Neutron stopper
  - Enhanced shielding

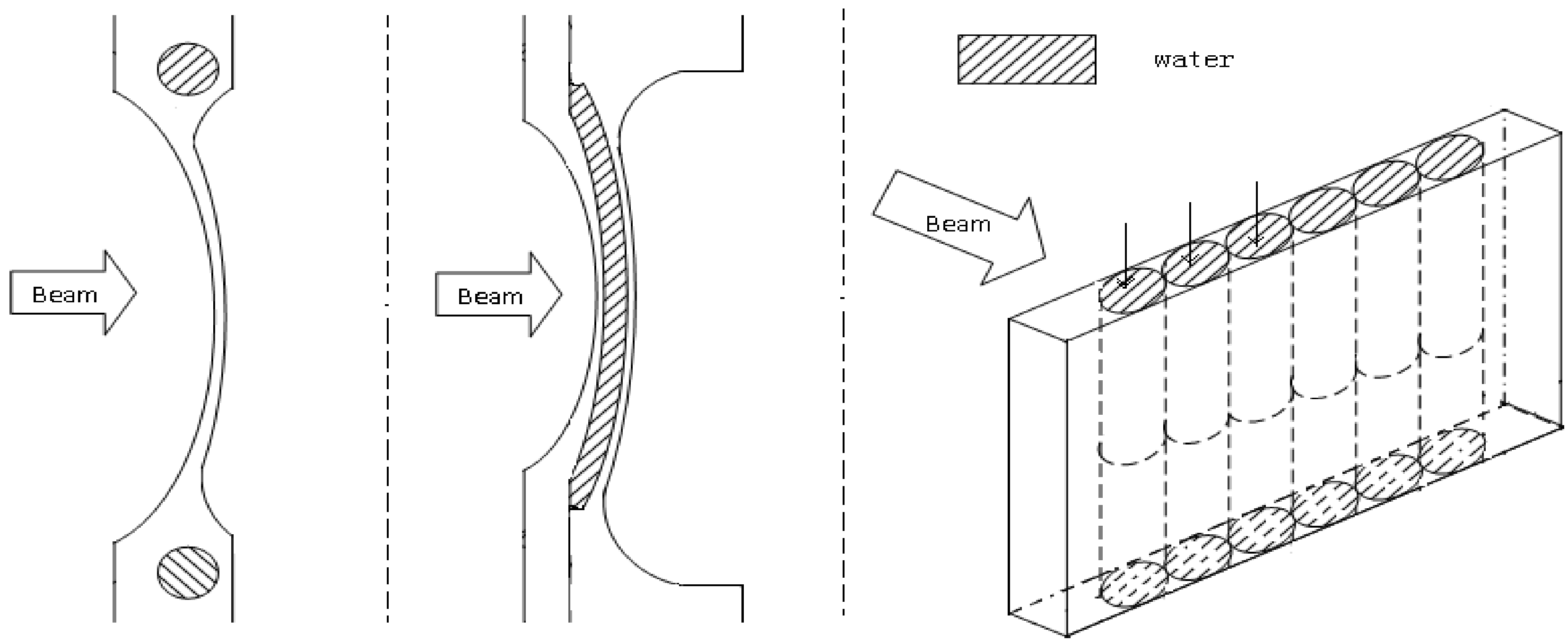


Proton beam windows

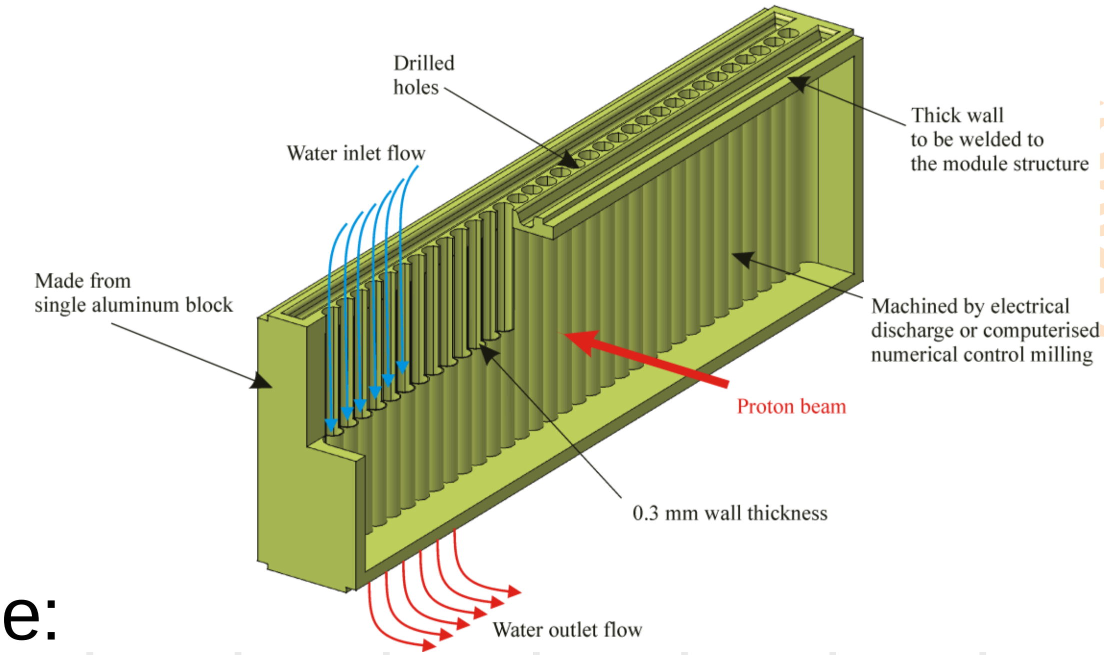
- With high power beams, proton beam windows (PBW) often pose technical problems, even more critical with beams of lower energy or pulsed beams
  - Heat deposit: Ionization process results in large heat deposit in PBW.
    - Water cooling necessary
    - Aluminum alloy preferred due to lighter mass and good thermal conductivity (J-PARC and CSNS, c.f. Inconel 718 used at ISIS and SNS)
    - Different beams, different structures: single layer (indirect cooling), sandwiched structure and multi-pipe structure from hundreds kW to MW
    - Pulsed beam is relatively more difficult than CW beam (temperature rise and larger pressure in a pulse)

Material and Structure

Material	Aluminum alloy （A5083-O）	Inconel 718	Stainless steel 316L
Density	2.66 g/cc	8.19 g/cc	7.99 g/cc
Thermal conductivity	117 W/m-K	11.4 W/m-K	21.4 W/m-K
Linear, CTE (coefficient of thermal expansion)	16.0µm/m-° C	13.0µm/m-° C	19.9 m/m-° C
Specific heat capacity	0.900 J/g-° C	0.435 J/g-° C	0.500 J/g-° C
Tensile strength, yield	145 MPa	980 MPa	290 MPa
Tensile strength, Ultimate	290 MPa	1100 MPa	558 MPa
Modulus of elasticity	70.3 GPa	204.9GPa	193 GPa

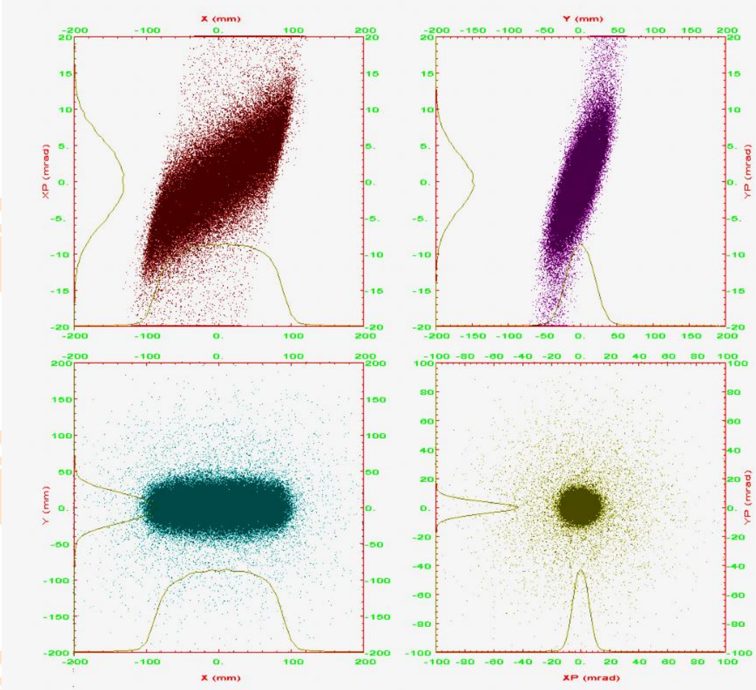


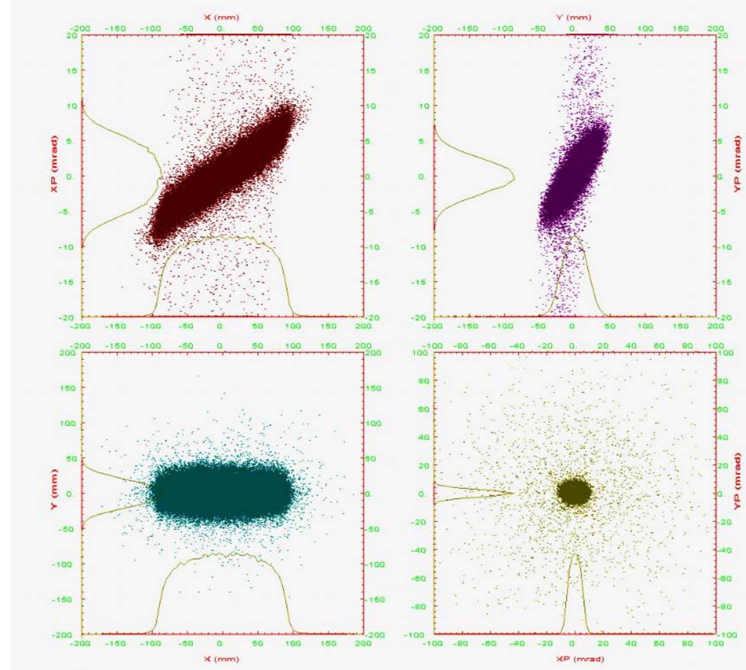
(a) single-layer structure (b) sandwich structure (c) multi-pipe structure



- Radiation damage:
  - Both aluminum alloy and Inconel are good materials for radiation resistance (20 dpa and 10 dpa, resp.)
  - More or less uniform, not too small spot at PBW is important (better close to target)
  - Also suffering irradiation from back-streaming neutrons (especially flanges)
  - Replaceable but better with longer lifetime (a few years), a plug inside target shielding wall

- Multiple scattering: PBW deteriorates beam quality at target by multiple scattering effect.
  - Larger mass thickness, lower energy and longer distance from target➔ more serious (also favor Al-alloy)
  - Fraction beam outside the target: e.g. about 4% @SNS
  - Damage target vessel (lateral)
  - Heating cold moderators





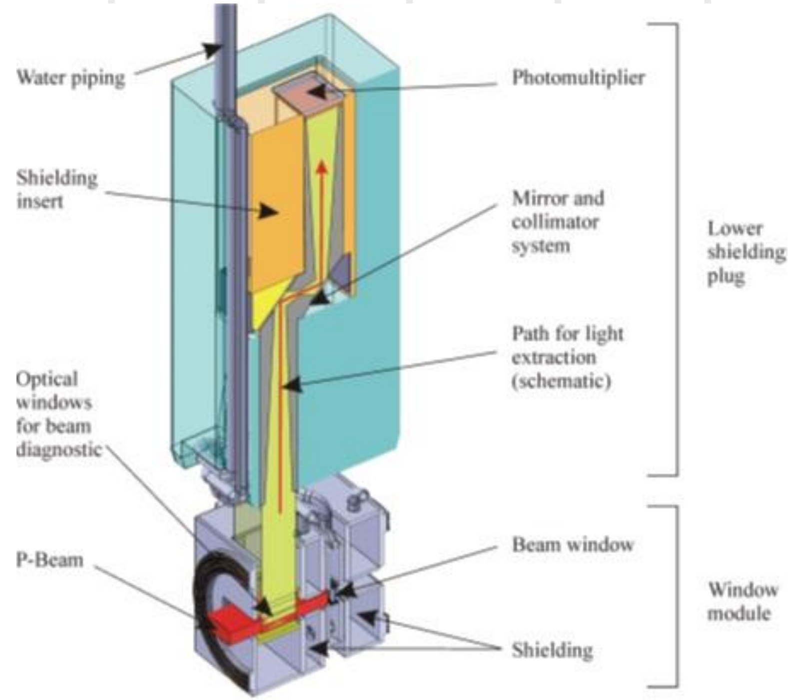
E=1.334 GeV, Sandwiched, Inconel @2 m (left); Aluminum alloy @1m (right)

- Some preferences
  - Aluminum alloy is an excellent material for PBW, but the maximum temperature should be controlled below 90-100°C to maintain its good mechanical properties.
  - Structures
    - Single-layer indirect cooling structure is the simplest one, but perhaps stands for beam power less than 200 kW (in GeV level)
    - Sandwiched structure can stand for beam power up to 1-2 MW
    - Multiple-pipe structure can stand for beam power up to 10-20 MW depending on beam size
  - Location: it is better to locate PBW closer to target to reduce the peak current density and scattering effect, e.g. 1-2 m.

Beam diagnostics in radiation-hard region

- As high-power beams are very destructive if they deviate from the designed footprint (beam center and spot size), online monitoring is necessary for the beam on target. Tuning procedures (especially with nonlinear magnets) also need beam monitoring.
- Online monitoring (BPM, profile) in radiation-hard region is difficult: probes, electronics, mechanical driving system
  - Probes: radiation-resistant, non-interceptive
  - Electronics: light transfer preferred (electronics outside channel, residual gas), how about BPM/harps?
  - Driving system (harps): remote control, easy demounting

- Tuning diagnostics
  - During beam commissioning and beam setup, BPMs and profile monitors are needed for the optics setup. They stay in the proton channel and suffer intense back-streaming neutron irradiation.
- Footprint monitor at target
  - VIMOS (tantalum mesh) @PSI
  - Coated frame @SNS
  - Thermal image @ISIS
- Profile monitor
  - Harps: @SNS, J-PARC
  - Residual gas – light (ESS@2002, IFMIF)



Summary

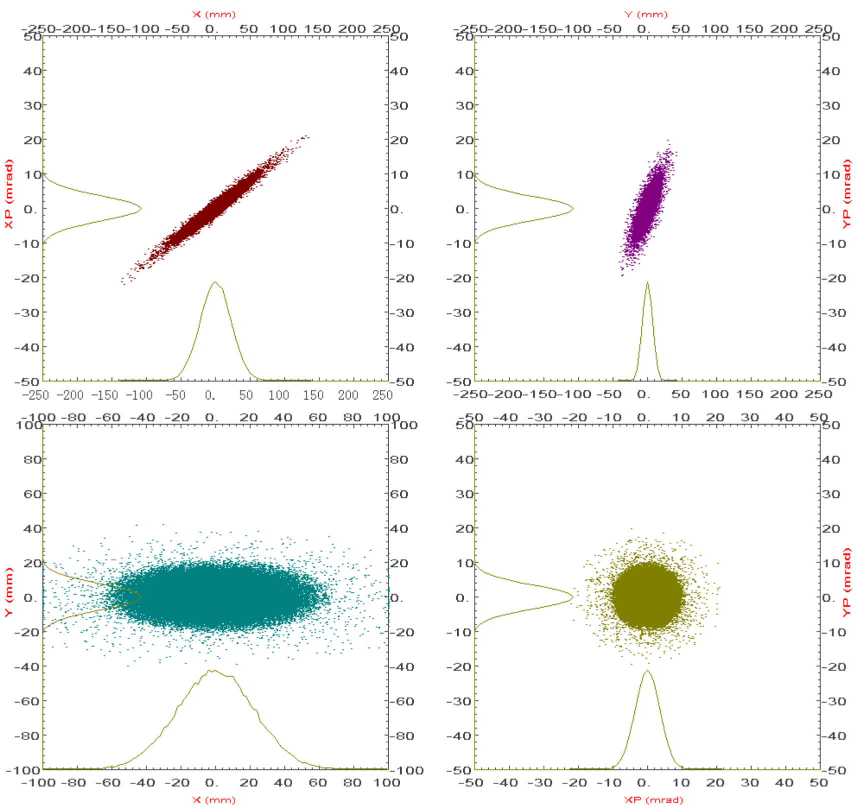
- Major problems concerning high-power beam on target are reviewed.
- Beam less than a few MW looks to be manageable, but it needs more efforts to solve ADS cases.
- International collaborations are needed to tackle the problems, especially with multi-MW beams in the future.

Thank you for attention!

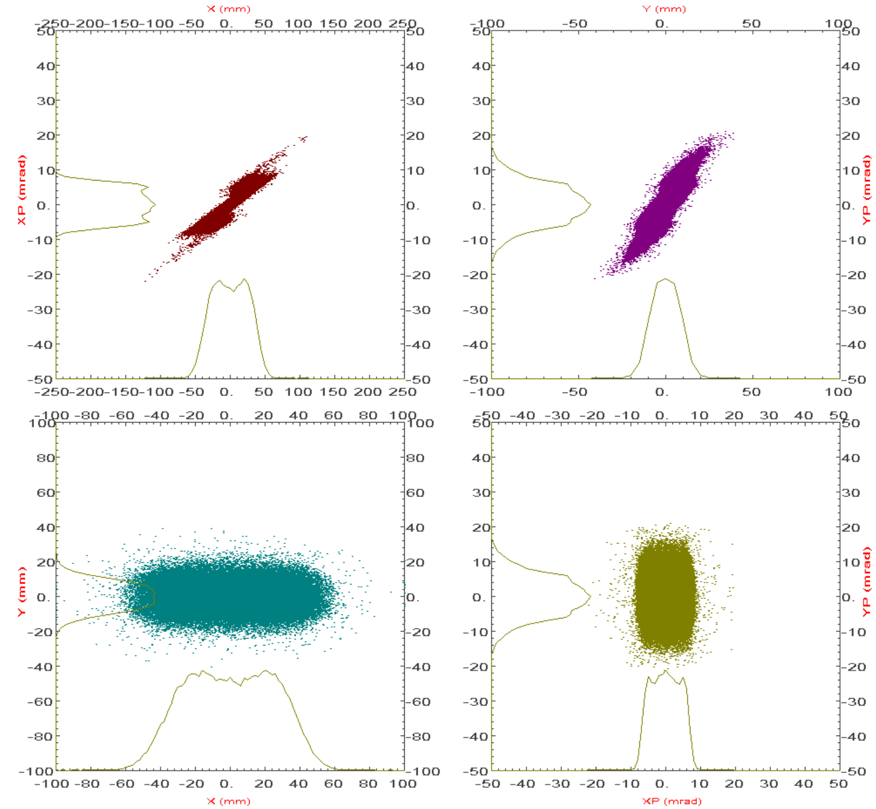
Comparison among nonlinear magnets for spot uniformization

	Pros	**Cons**
SFM	Very cheap (cost + electricity) Almost no beam loss Space saving (very short) Neat beam at waist (collimation) Small gap (as neutron collimator)	Slightly less tunability Small gap (tuning) More complicated vacuum chamber
Single Octu	Simple to apply (tuning procedure) Modest cost	Worse performance Beam loss important
Octu+Dodeca	Good performance Modest beam loss	High cost More space
Simplified Sextu+Deca (or Octu)	Cheap Very good performance Modest beam loss	In between SFM and Octu+Dodeca

Using a single SFM



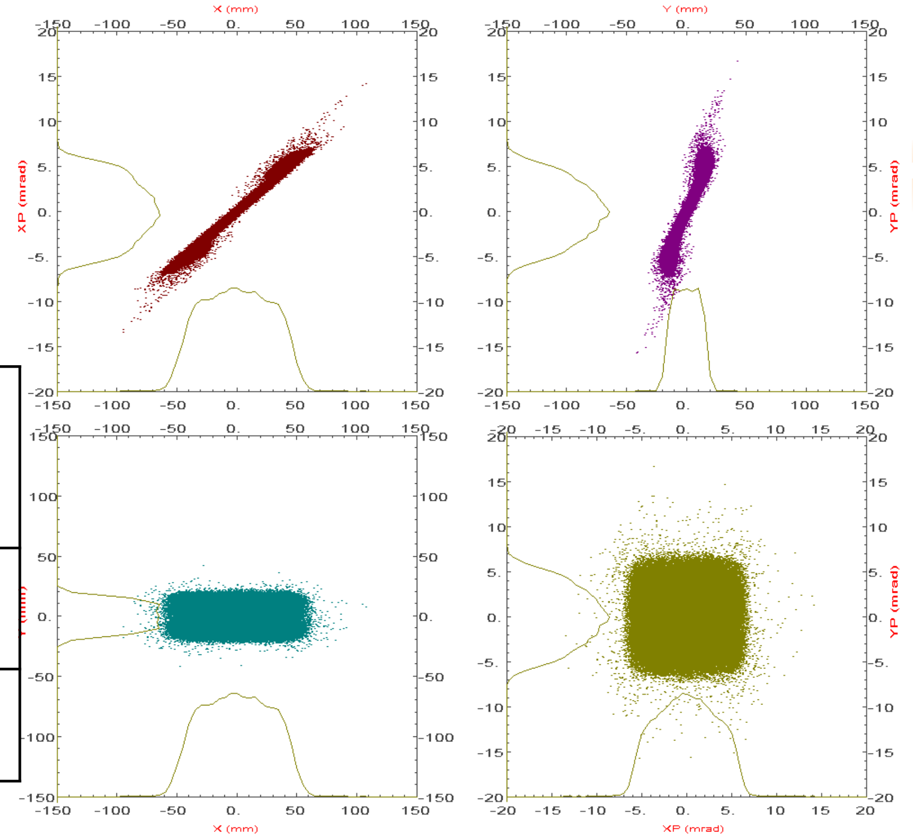
Without SFM



With single SFM

CSNS-I (100 kW)

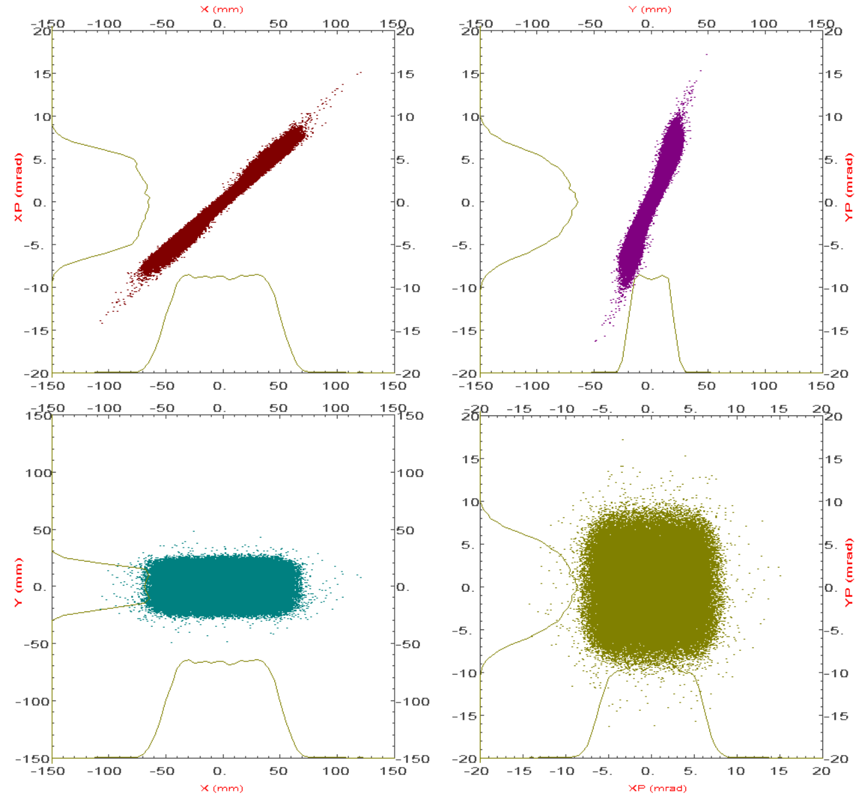
Dual-Gaussian ($\pm 3\sigma$, πmm.mrad)	Emitt	Raw portion	Real portion
Core beam	60	97%	98.6%
Halo beam	250	3%	1.4%



	B (T)	L (m)	x0 (mm)	b (1/mm)
SFM-X1	0.135	0.20	35.8	0.14
SFM-X2	0.120	0.15	59.7	0.15
SFM-Y1	0.100	0.20	28.6	0.16
SFM-Y2	0.133	0.18	47.7	0.14

CSNS-III (500 kW)

Dual-Gaussian ($\pm 3\sigma$, πmm.mrad)	Emitt	Raw portion	Real portion
Core beam	105	97%	98.9%
Halo beam	250	3%	1.1%



	B (T)	L (m)	x0 (mm)	b (1/mm)
SFM-X1	0.095	0.20	35.8	0.14
SFM-X2	0.060	0.15	59.7	0.15
SFM-Y1	0.060	0.20	28.6	0.16
SFM-Y2	0.090	0.18	47.7	0.14

- When halo emittance is very large, one can consider using a third step
- Right: ESS-2002, with two steps for ring beam