

Achieve a record dynamic range of halo diagnostics with a novel fluorescence wire concept

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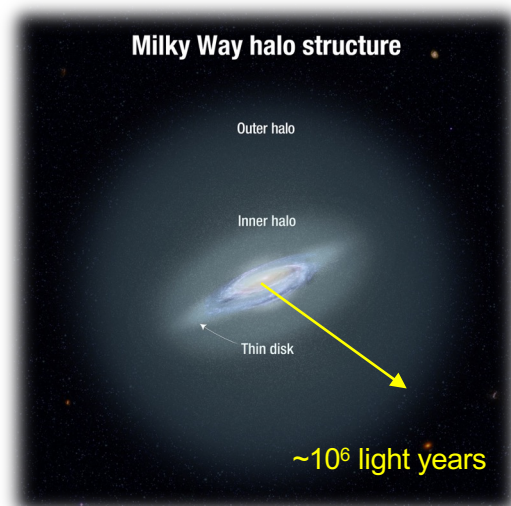
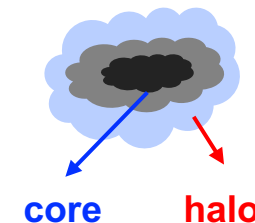
21/05/2026
Deauville, France

Halo: from galaxy to accelerator



Observation and characterization of halo can uncover many mysteries of our universe!

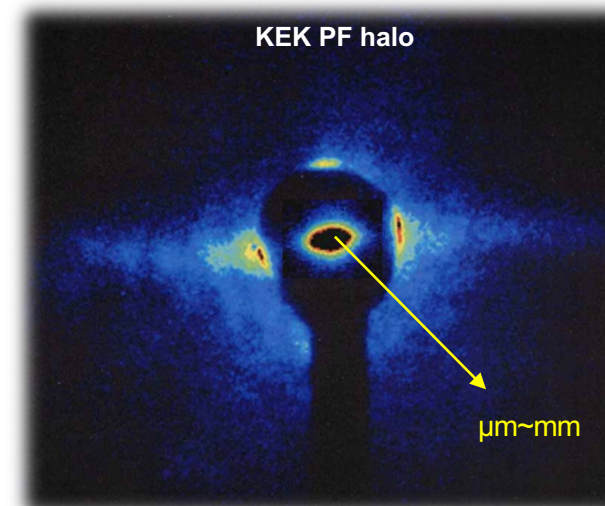
Halo diagnostic is extremely hard, and an instrument with a satisfactory contrast is essential!



A galactic halo is an extended, roughly spherical component of a galaxy which extends beyond the main, visible component. Several distinct components of a galaxy comprise its halo: the stellar halo, the galactic corona (hot gas, i.e. a plasma), the dark matter halo



Sun corona extends for millions of miles and roils with plasma, gases superheated. The corona is ~ 10 million times less density than the sun surface, but hundreds time hotter.



The beam halo extends far from beam core and at 10^{-4} to 10^{-6} level and below.

* K. Wittenburg, DESY, Beam Halo Monitoring, CAS Beam Instrumentation, 2018

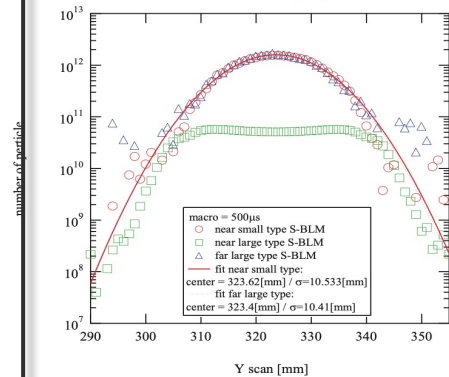
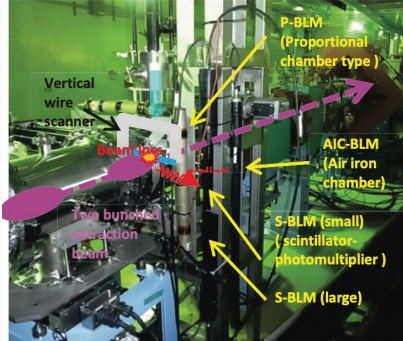
[1] <https://news.ucsc.edu/2023/01/milky-way-halo.html>

[2] <https://www.nasa.gov/science-research/heliophysics/nasas-parker-solar-probe-and-the-curious-case-of-the-hot-corona/>

[3] T. Mitsuhashi, Coronagraph for diagnosing beam halo, HALO'13

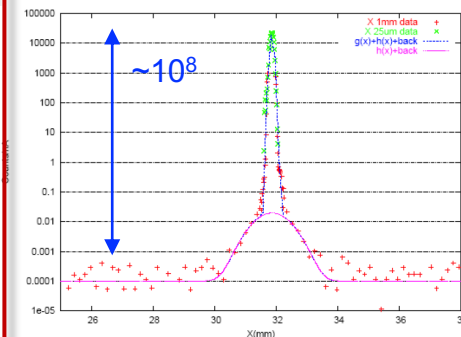
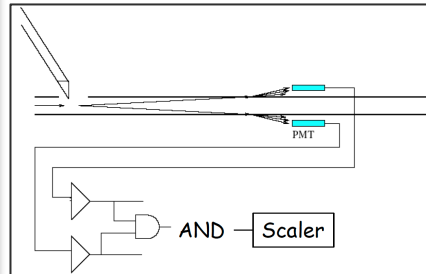
Direct halo diagnostics – scanner

WS+FBLMs @J-PARC



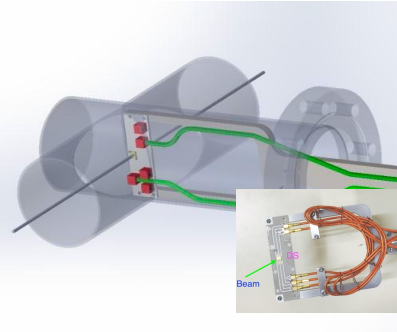
M. Yoshimoto, IBIC2015

$\sim 10^8$ DNR with WS and coincident counting @JLab

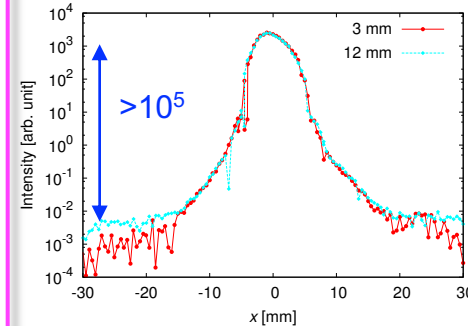


A. Freyberger, DIPAC2005

sCVD diamond strips ($0.1 \times 4 \text{ mm}^2$) @KEK-ATF

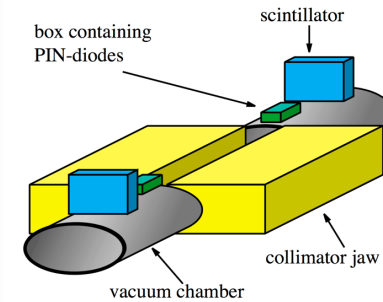


$\sim 10^5$ DNR with additional reconstruction of core

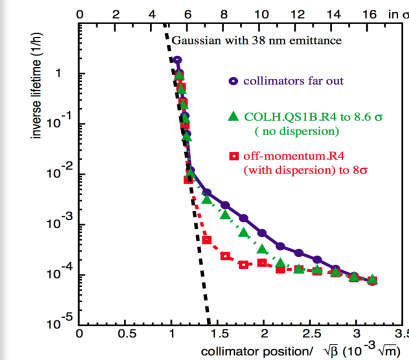


S. Liu et al., NIMA (2016)
R. Yang et al., PRAB (2018)

Halo scraper + diode/scintillator @LEP

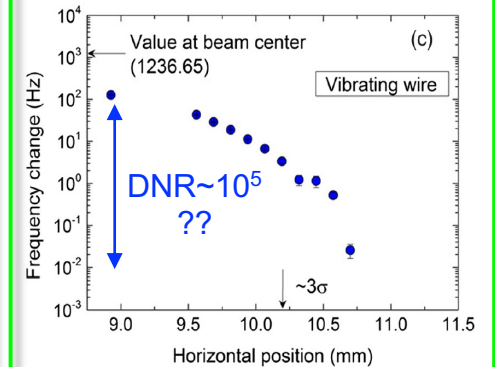
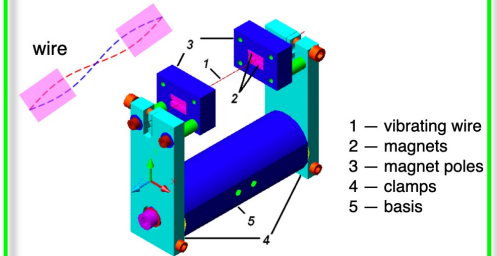


Max. DNR $\sim 10^5$



H. Burkhardt et al., PRST-AB (2000)

Vibrating wire scanner proposed by S. Arutunian

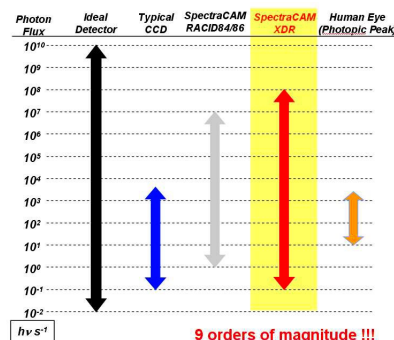
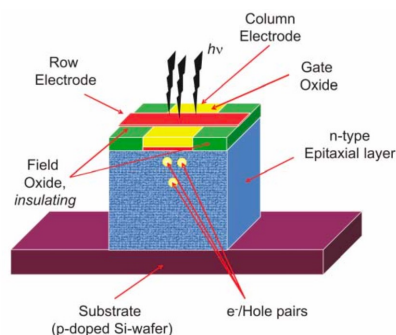


S. Arutunian et al., PRST-AB (2014)

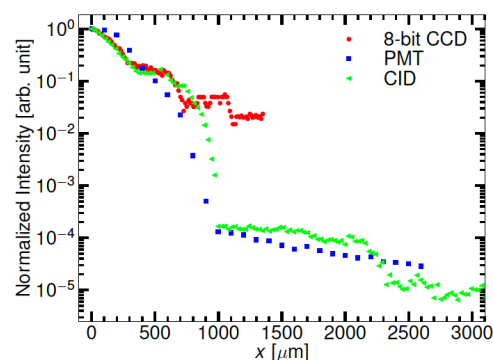
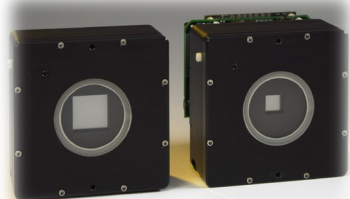
[1] K. Wittenburg, CAS Beam Instrumentation, 2018

Direct halo diagnostics – optical method

- The commercial charge injection device (CID) features a dynamic range exceeding 10^6
- Experiments in lab have indicated a dynamic range $>10^5$
- But, CID camera is embargo to many countries

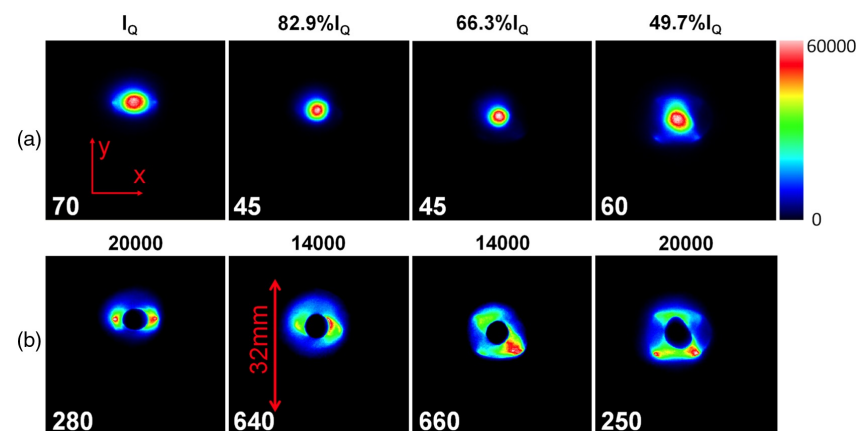
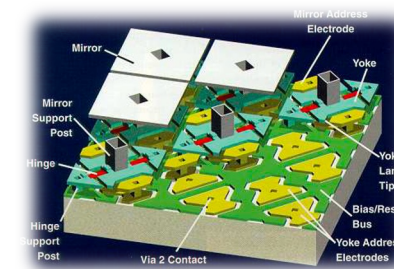
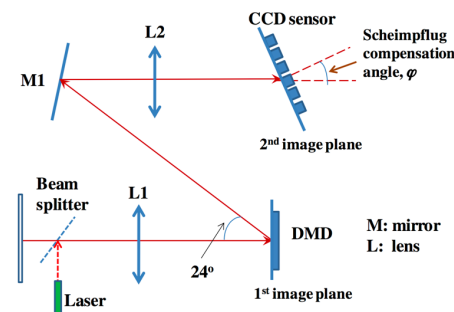


SpectraCAM™



* C. Welsch et al., Meas. Sci. Technol. 17 (2006)

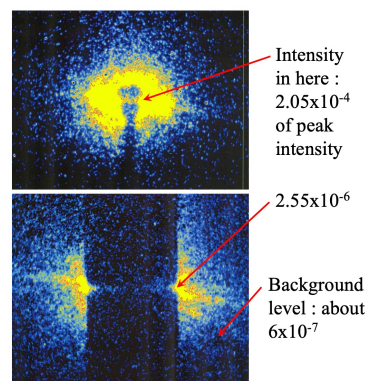
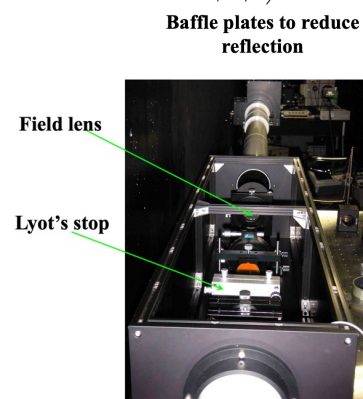
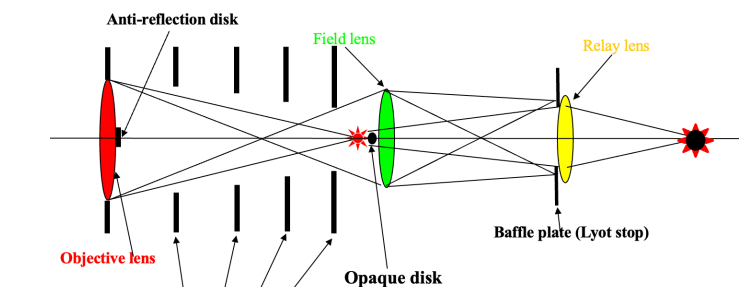
- Digital micromirror device (DMD) to form a blocking mask to filter out the core image (suppress the diffraction light)
- A dynamic range of $>10^5$ @ UMER
- Applied to SPEAR3, JLab FEL and Australian synchrotron



* H. Zhang et al., PRST-AB (2012)

Direct halo diagnostics – optical method

- A coronagraph with a Lyot stop to remove the diffraction light from bright core
- SR or OTR as source light
- A background level of $<10^{-6}$ and spatial resolution of $\sim 50 \mu\text{m}$ have been demonstrated
- KEK PF, LHC, SuperKEKB ...



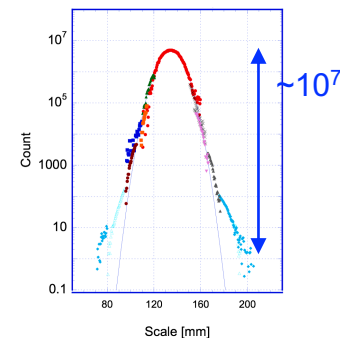
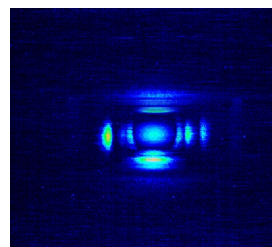
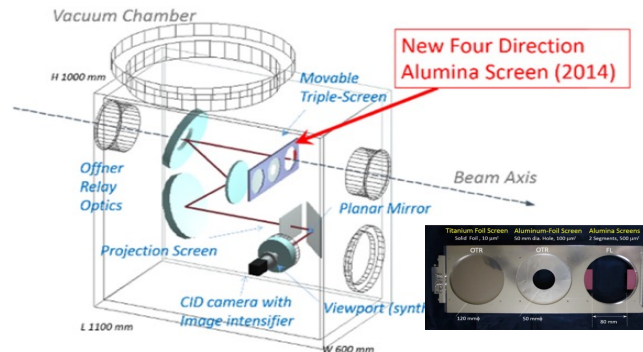
* T. Mitsuhashi, DIPAC 2005

** T. Mitsuhashi, Beam-halo monitoring workshop (2014)

- To mitigate the image blurring and light diffraction due to bright core, we can instead image core & halo parts individually

OTR+fluorescence screen @J-PARC

- Offner relay system; Intensifier+CID camera; beam size $\sim \text{mm}$
- Max. DNR $\sim 10^7$ (1D)

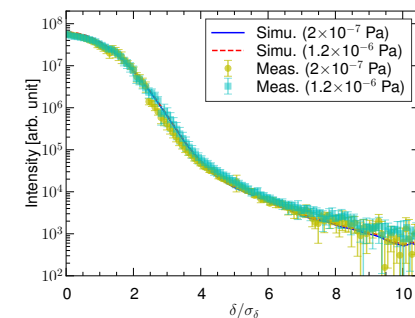
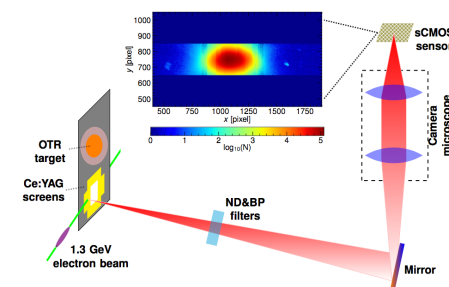


* Y. Hashimoto et al., IBIC2013

** Y. Hashimoto et al., HB2014

OTR/YAG screen @KEK-ATF

- Microscope + sCMOS camera beam size $\sim 100 \mu\text{m}$
- Max. DNR $\sim 10^5$ (1D, $\sim 5 \times 10^9$ ppb) using only the YAG screen



* R. Yang et al., PRAB (2025)

Halo diagnostics at CSNS LINAC

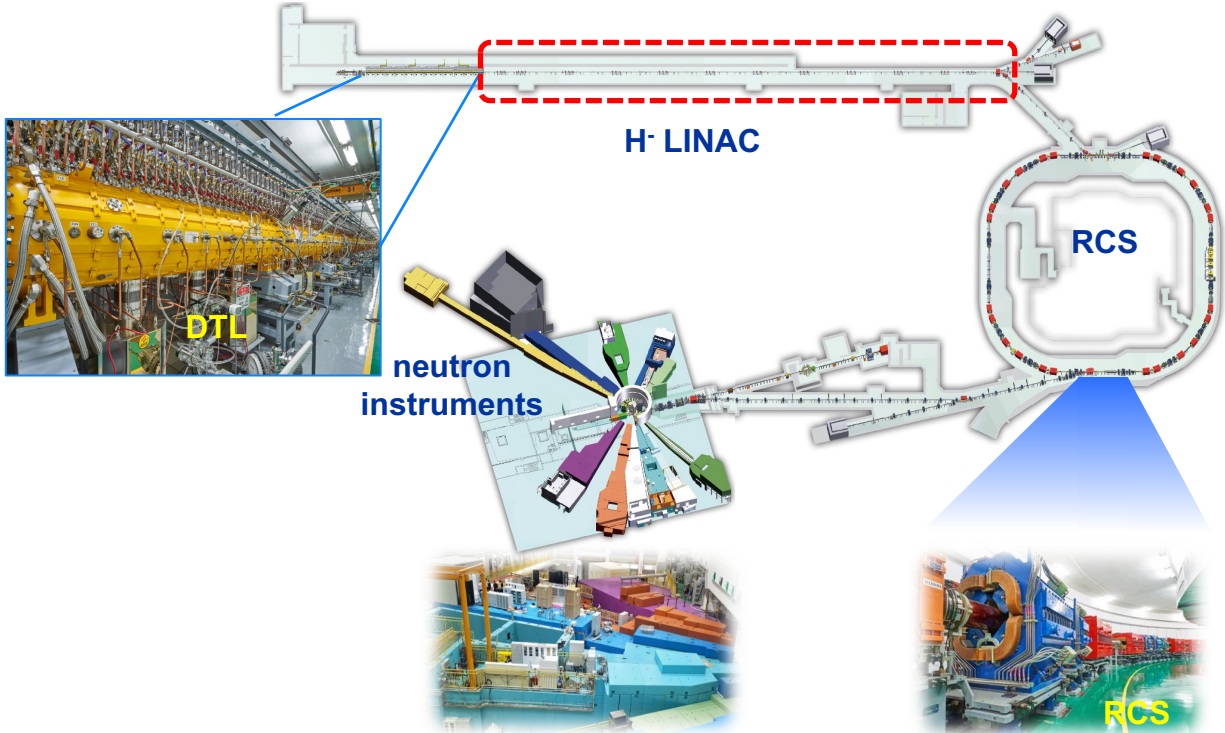
China Spallation Neutron Source



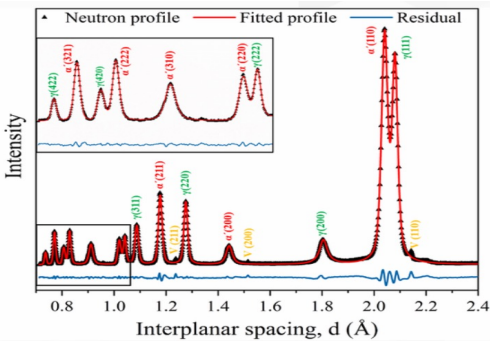
- The 4th pulsed neutron source in the world
User program started since October 2018
- 3 initial instruments (GPPD, MR & SANS) +
8 cooperative instruments
- **CSNS-II (2024-2030): beam power ramp up to
500 kW + 9 new neutron instruments + μ -source**

Major machine parameters

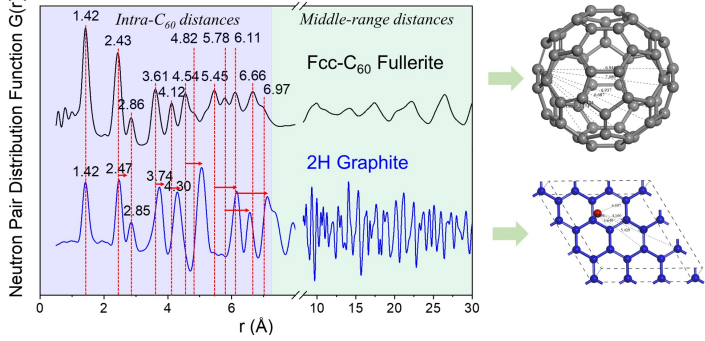
	CSNS	CSNS-II
Beam Power on target [kW]	185	500
Proton energy [GeV]	1.6	1.6
Average beam current [μ A]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	300
Macropulse. ave current [mA]	15	50
Linac bunch frequency [MHz]	324	324



Liu et.al. Science (2020)



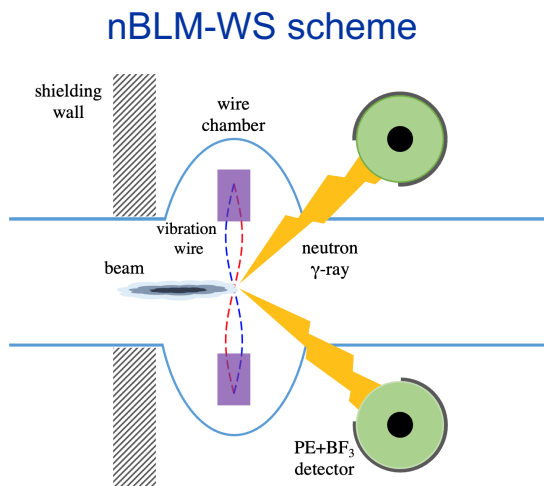
F. Pan et.al., Nature (2023)



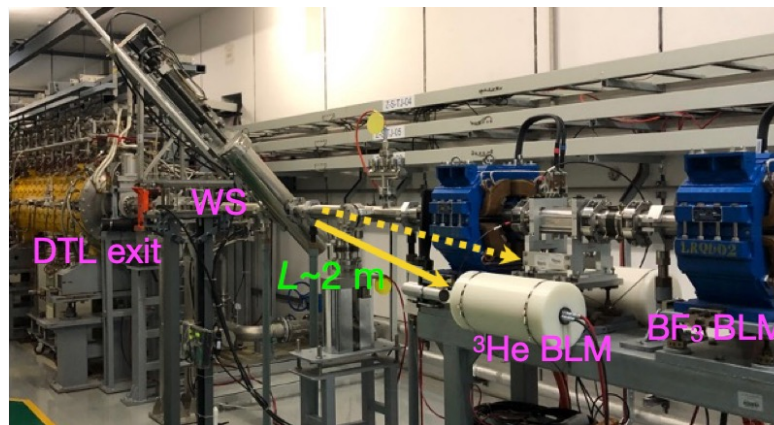
WS + Neutron sensitive BLM



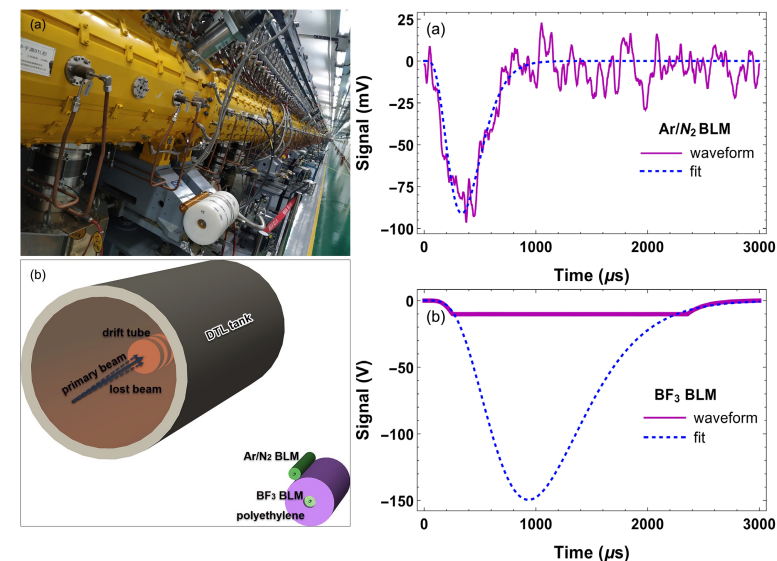
- Many profile monitors could be extended to high dynamic-range (DNR) beam halo monitors. We define an optimum solution concerning *technical reliability, max. capability, cost, reusability, etc.*
- Towards a goal DNR of 10^5 - 10^6 , our first strategy is a combination of WS and nBLM
 - A BF_3 coaxial ionization chamber (1 atm) with a $\sim 10^4$ higher sensitivity than the regular Ar/N_2 ICs at CSNS
 - To improve the SNR, the tungsten wire has been updated ($\phi 30 \mu\text{m} \rightarrow \phi 100 \mu\text{m}$)



First demonstration at DTL exit (80 MeV)



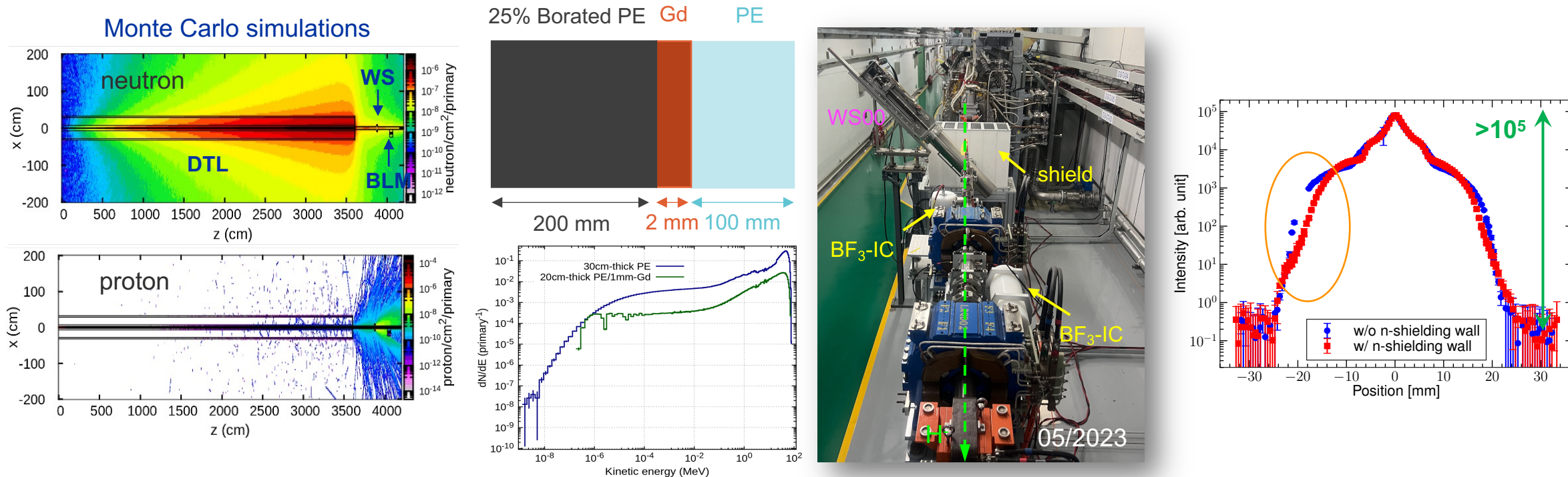
Experiment at CSNS DLT



[1] T. Yang et al., PRAB 24, 032804 (2021)

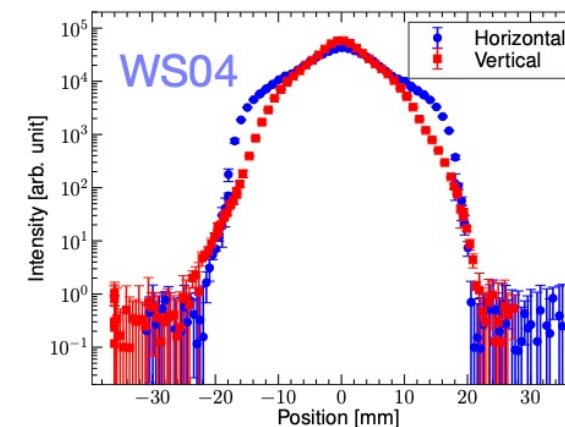
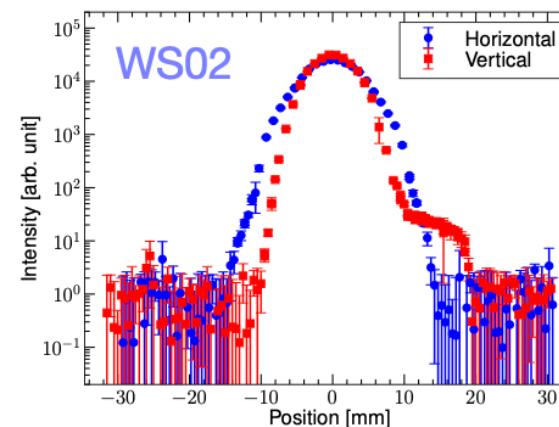
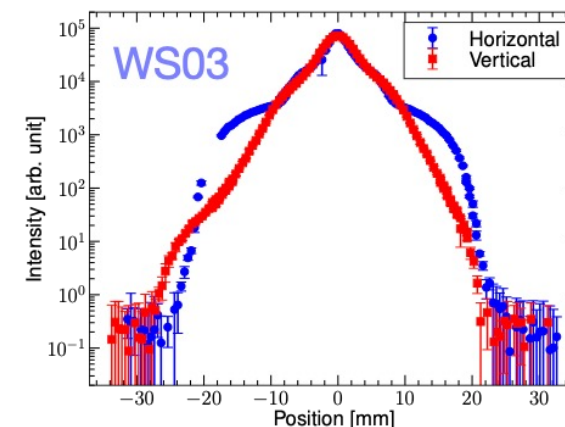
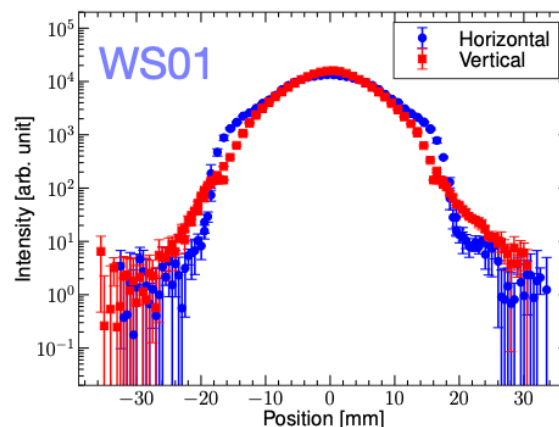
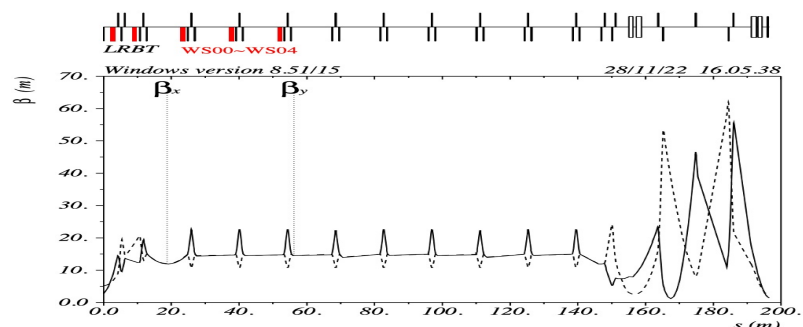
Shield of background neutrons

- Instead of the detection efficiency, the noise level (signal fluctuation) around the nBLM hampers the improvement of the DNR to more than 10^5
- A shield block ($800 \times 600 \times 302 \text{ mm}^3$) made of borated-PE, Gd and PE was then placed upstream of the WS
- The nBLM signal in the tail/halo parts are reduced, and a DNR of $\sim 10^5$ is sequentially established



Application: a multiple WS halo monitor

- By placing a BF_3 -IC downstream (1~2 m) of each WS along the transport beamline, a multiple WS halo monitor have been completed. The dynamic range is $\sim 10^5$ depending on the upstream beam-loss control
- Picture the 1D halo distributions (hor. & ver.) at different β -tron phases (hints of mismatch?)

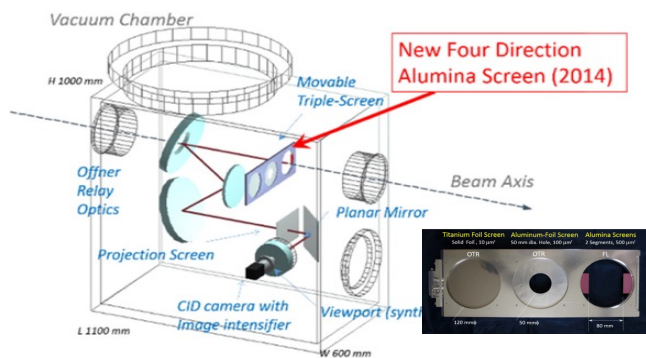


Concept of a fluorescence wire scanner

- Wishlist for a large-dynamic-range beam halo monitor for a high-intensity p+ accelerator
 - Least perturbation to the beam and high tolerance to beam damage: WS, non-invasive methods
 - High sensitivity, low background noise: optical methods (fluorescence material, $\sim 10^4$ ph/MeV)
 - Radiation hard
 - Simple and cheap (use commercial devices)

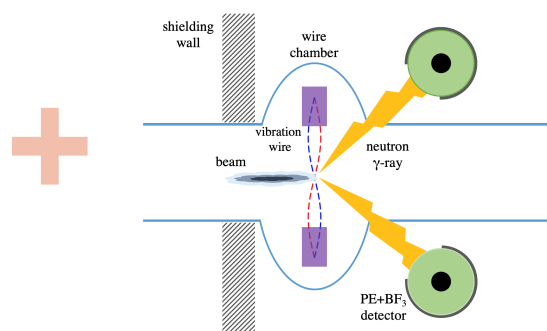
- Great DNR and sensitivity, but incomplete 2D image; beam loss after inserting screens

➤ Thin strip/wire



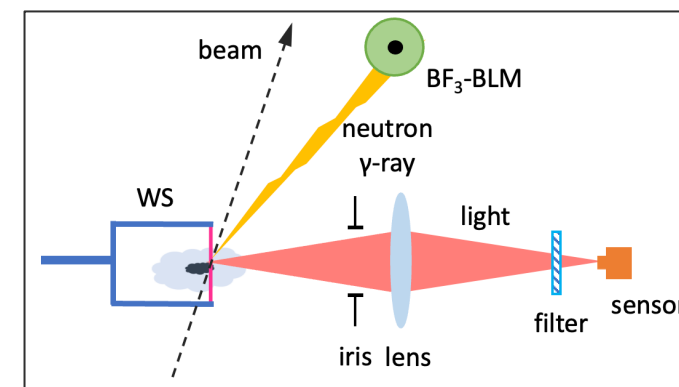
- Small perturbations to beam ($\propto$ wire diam.), simple, rad. hard
- A fair DNR limited by background neutron & γ -ray noise

➤ Combining optical method



Fluorescence wire scanner (FWS)

- Core & tail: WS-nBLM scheme
- Halo: fluorescence light collection (2D image not necessary, light flux $\propto$ wire thickness)
- no diffraction light from beam core



Fluorescence wire material selection



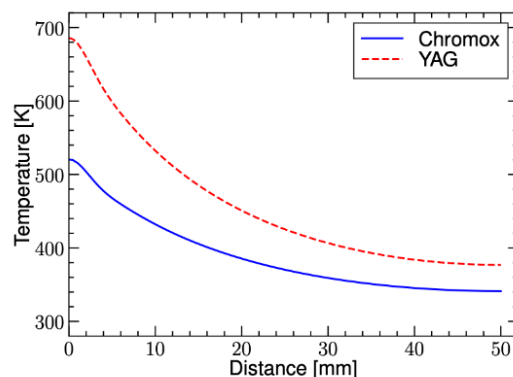
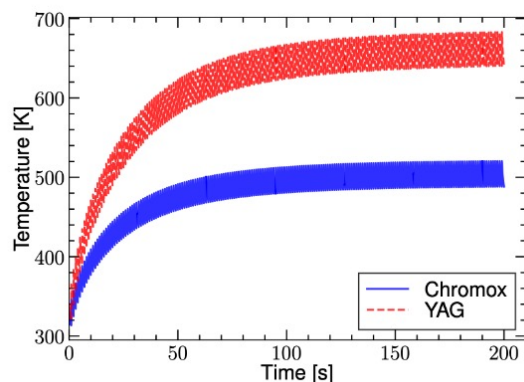
- Good mechanical and thermal properties
 - Storage, transport, installation (ceramic material...), thermal load
- Radiation resistance
- A thin wire diameter to control beam loss ($< 1/5 \sigma_{x,y} \sim 0.2 \text{ mm}$)
- Wire length should be much larger than beam size ($\pm 20 \sigma_{x,y} \sim 100 \text{ mm}$)

	Chromox	Ce:YAG	GAGG
Density (g/cm ³)	3.85	4.57	6.63
Wavelength (nm)	691/694	550	520
PhY (ph/MeV)	5×10^4	2×10^4	5×10^4
Transmission	~ 0.8	0.8	~ 0.8
Melting point (°C)	2000	1970	1850

ANSYS simulations

H⁻ beam, 80 MeV, 10 mA, 100 μ s, $\sigma_{x,y}=2 \text{ mm}$; wire size $0.2 \times 1 \times 100 \text{ mm}^3$

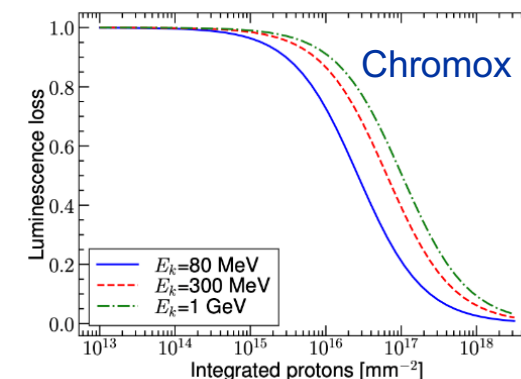
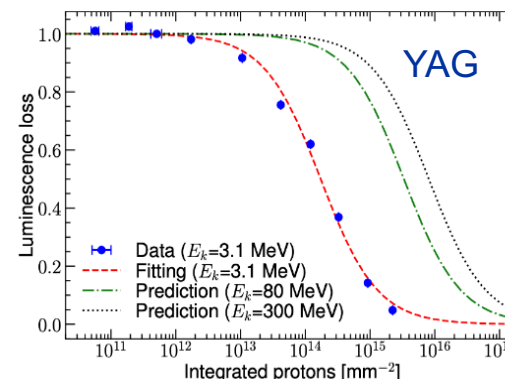
=> $T_{\text{max}} < 1000 \text{ K}$ for both Chromox(Cr:Al₂O₃) and YAG



Luminescence degradation

Evaluated employing a model proposed by J. Briks and the Ce:YAG experiments at 3.1 MeV

Results: $n_{1/2, \text{chromox}} > 10 \cdot n_{1/2, \text{YAG}} \sim 10^{15} \text{ mm}^{-2} @ 80 \text{ MeV}$



[1] J. Briks, Proc. Phys. Soc. A 64 (874), 1951

[2] P. Novotny et al., JINST (2017)

Eventually, Chromox-6 is selected for the PoP experiments!

Design of FWS prototype

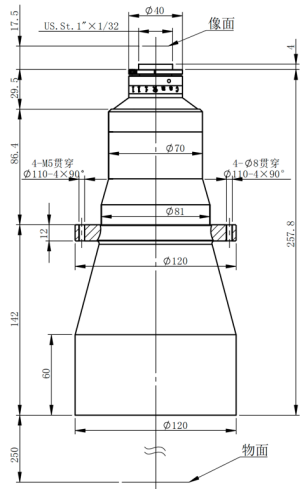
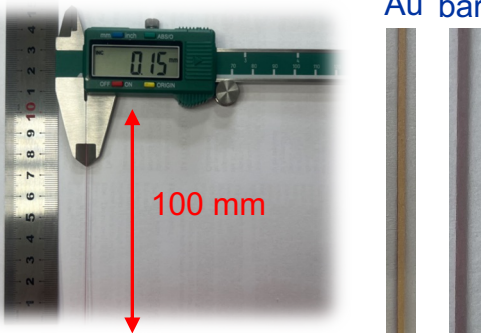


- Thanks to the waterjet cutting technique, we succeed to manufacture the Chromox-6 pad into wire
The min. width is 0.15 mm ($0.15 \times 1 \times 100 \text{ mm}^3$), and 0.2 mm wide strip is used
- Au coating (100 nm) on the backside was later applied, aiming to additionally collect the back-reflected light
- For the PoP experiments, a telecentric lens+CMOS camera was used

Waterjet cutting machine



Au bare



Specifications

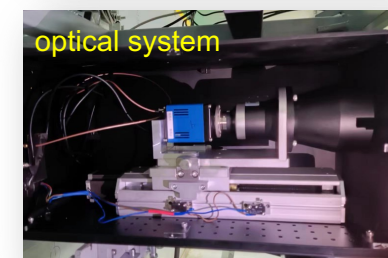
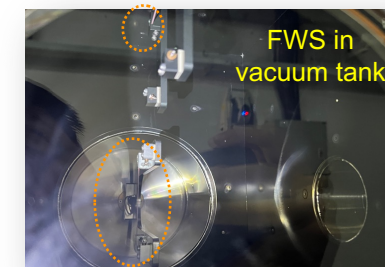
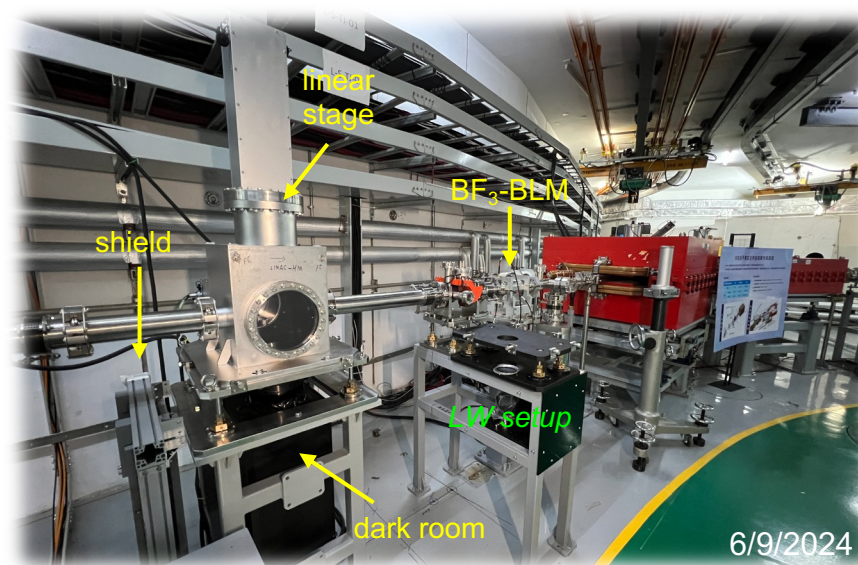
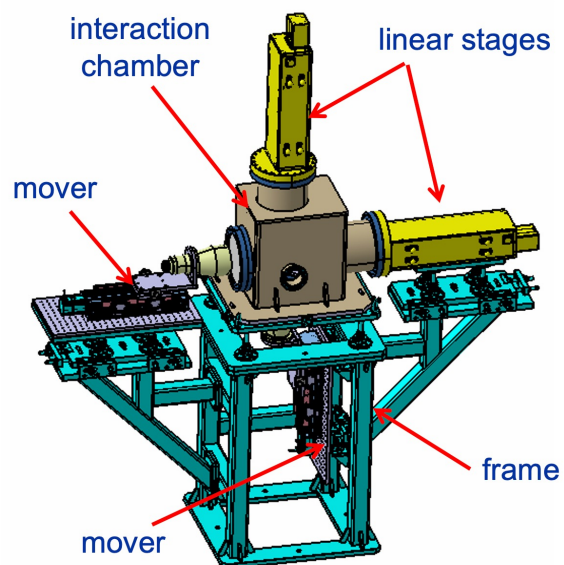
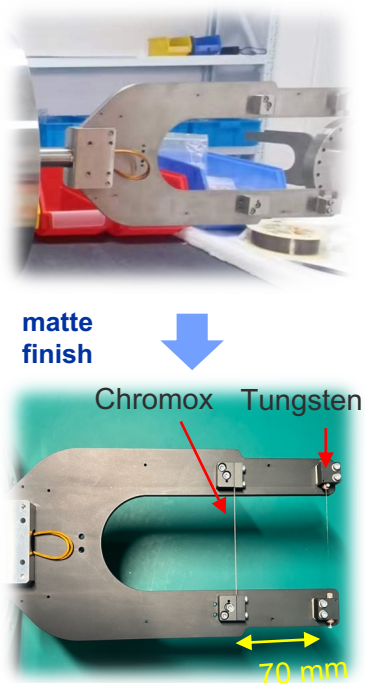
Work distance (mm)	250
Magnification	0.087
FoV (mm)	91.5
Aperture (f/#):	F5.5
DoF (mm)	80
Resolution (μm)	41

	Pco.edge.42 LT	Pco.edge.5.5	Basler a2A4200
Pixel size [μm]	6.5x6.5	6.5x6.5	2.5x2.5
Readout noise [e-]	0.8	1.0	1.1
Max. capacity [e-]	3×10^4	3×10^4	4.6×10^4
Bit depth [bit]	16	16	12
Dynamic range [dB]	91.5	89.5	>60
QE	>70%@550 nm >50%@700 nm	~60%@600 nm >45%@700 nm	53%@500 nm ~27%@700 nm
Gain@700 nm [DN/ph/px]	>1.20	1	0.21
Norm. gain@700 nm [DN/ph/μm ²]	0.0283	0.0336	0.0237
Sensitivity threshold (SNR=1) [ph]	unknown	4.6@~600 nm 7.0@~700 nm	3.2@~500 nm 6.4@700 nm

[1, 2] AEON, EMVA1288 Data Sheet m0550 (2014)
[3] <https://www.baslerweb.com/zh-cn/shop/a2a4200-12gmpro/>, <https://docs.baslerweb.com/a2a4200-12gmpro>
[4] <https://www.baslerweb.com/en-us/shop/aca4112-8gm/>

Construction of FWS prototype

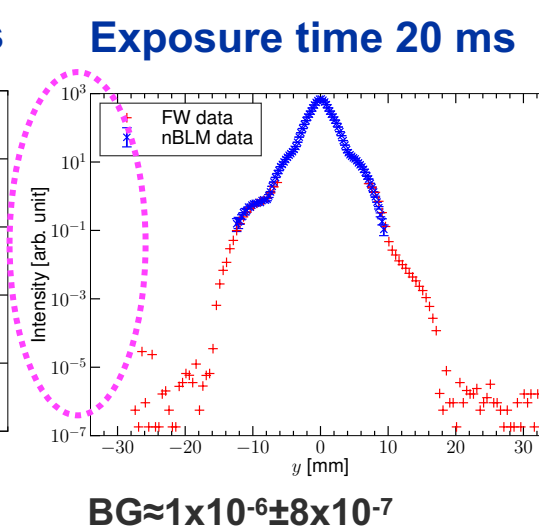
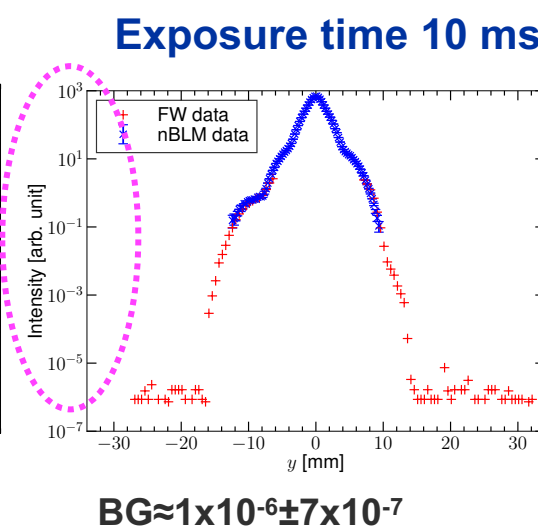
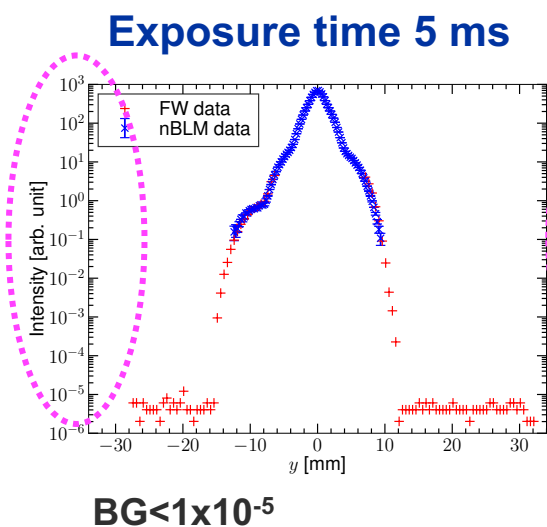
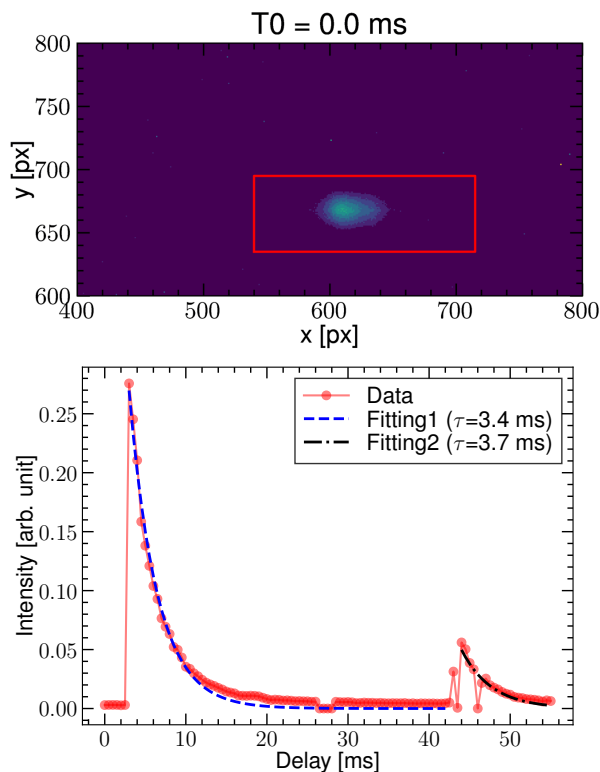
- To avoid quick luminescence degradation, a tungsten wire ($\phi 100\ \mu\text{m}$) has been appended
 - Core & tail: tungsten wire + BF_3 IC ($1:10^{-5}$)
 - Halo: fluorescence wire + light collection ($10^{-5}:\sim$)
- To reduce light reflection, the chamber and wire frame are matted
- A shield in front of the optical system to diminish radiation damage to camera



Commissioning remarks



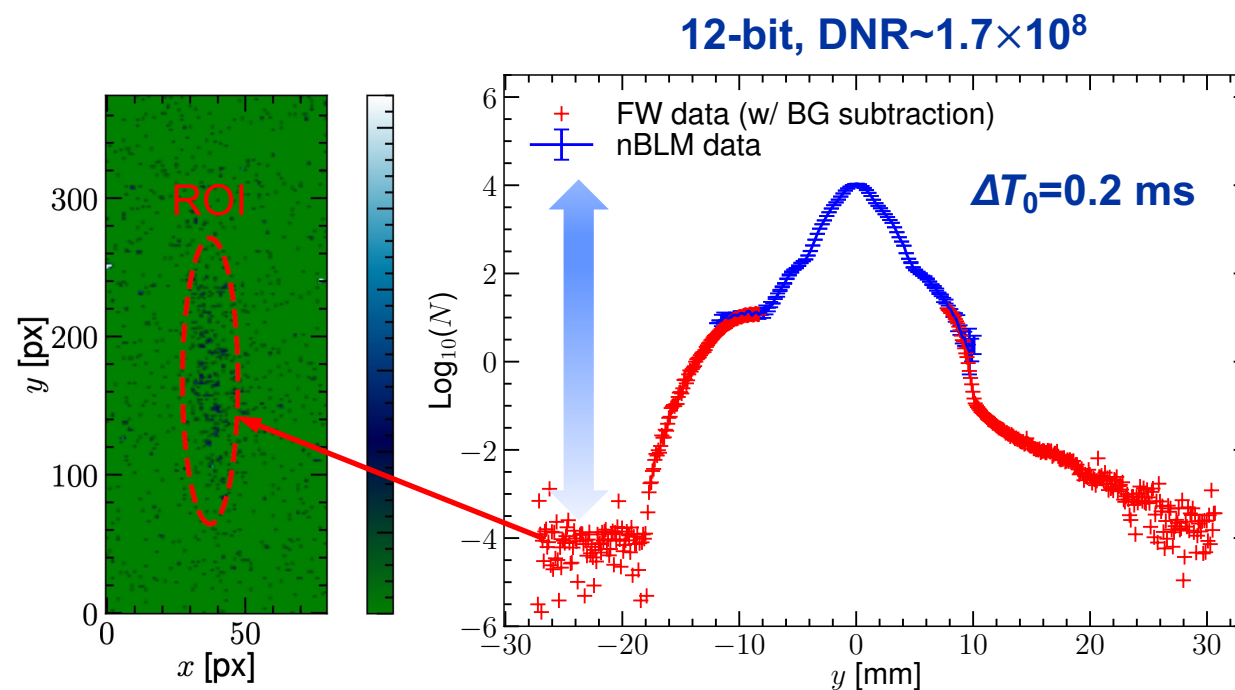
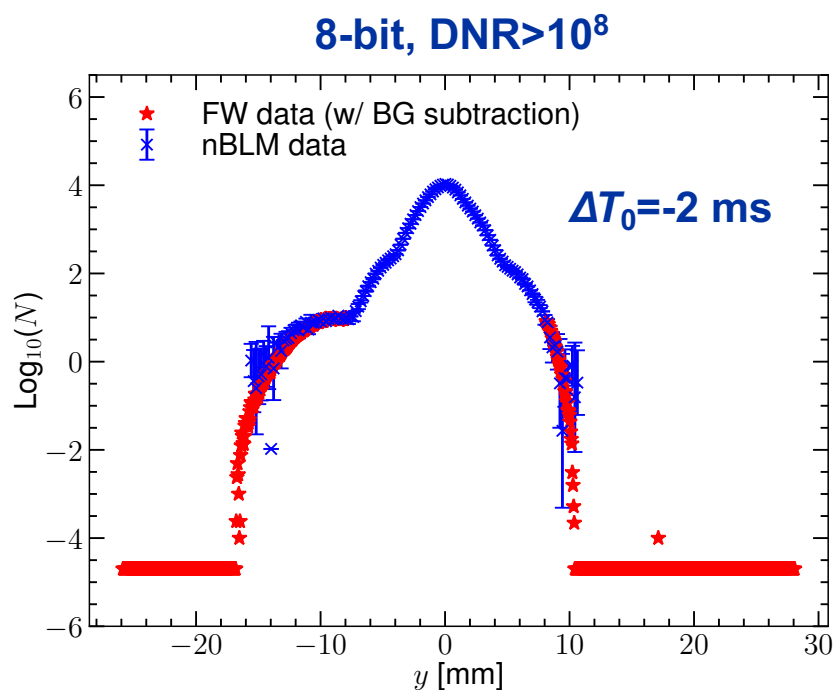
- The nominal decay time of Chromox-6 is ~ms level depending on the manufacture technology
 - With an exposure time of 100 μ s, a decay time of 3.4 ms has been confirmed
 - The afterglow around ~40 ms is suspected to be induced by the 2nd H⁻ pulse!
- Measurements with exposure time of 5, 10 and 20 ms indicate similar dynamic ranges of $>10^8$ (CMOS, 8 bit)
- **An optimized exposure time of 10 ms was used for later observations**



Commissioning remarks (cont')

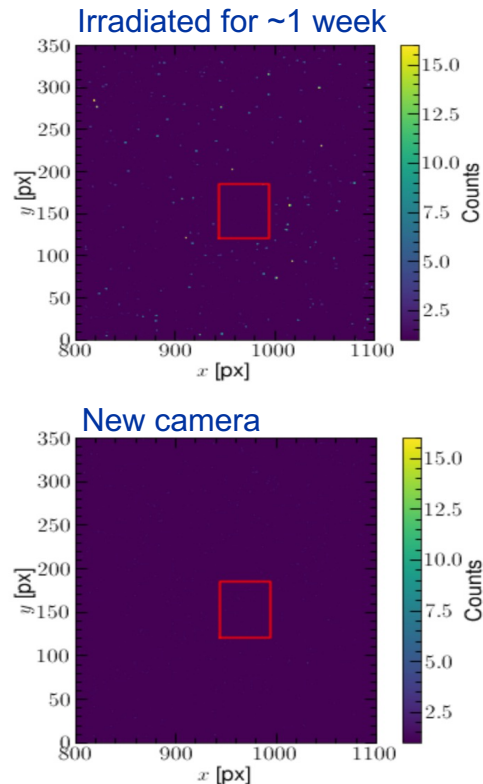


- A dynamic range of $>10^8$ has been obtained with 8-bit depth, hor./ver. binning=2/4 !!
- **After optimizing the T0 trigger timing to ~ 0.2 ms behind the H⁻ beam, a dynamic range of $\sim 1.7 \times 10^8$ has been successfully established at 12-bit depth!**
 - Determine the background level (DN/pixel) over ROI when the fluorescence wire is near home position
 - Combination (rescaling) of the nBLM and camera data wrt. the observed signal in the overlapping regions

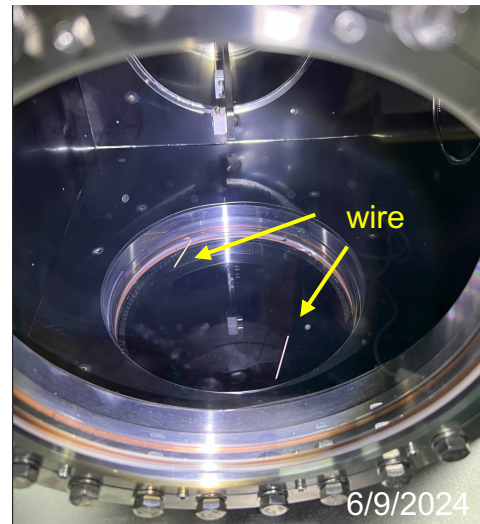


Lessons learnt and potential upgrades

- The irradiated camera shows visual discrete noisy pixels over the ROI
=> better shielding, regular replacement of camera, remove camera after experiment
- The fluorescence wire was damaged during operation probably due to thermal load (core particles)
=> advanced scan strategy (forced beam off before entering core region)
- **The transmission of Chromox-6 is likely much lower than the expectation!**



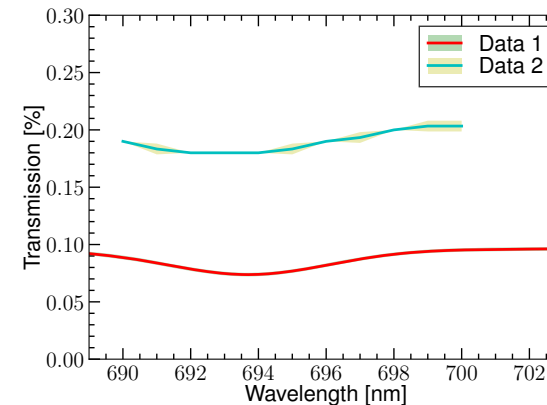
Damaged vertical fluorescence wire (beam induced!)



Attenuation co-efficient, α (mm⁻¹) @ 694 nm

0.8 ± 0.1

The attenuation coefficient of Chromox-6 was established as 0.8 ± 0.1 mm⁻¹, i.e., trans. ~0.2 w/ a thickness of 1mm



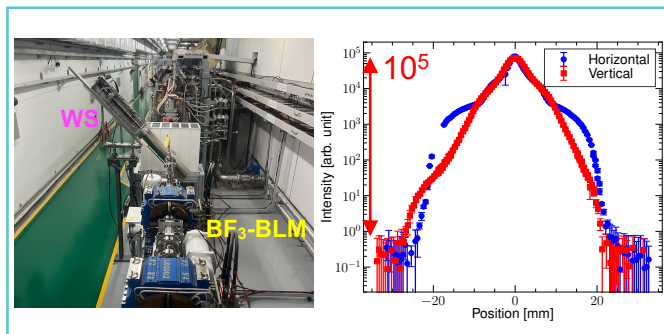
Measurements with different spectrophotometers show a trans. $\leq 0.2\%$ @ 1 mm !!
=> α (mm⁻¹) > 0.99
=> New fluorescence material, e.g., GAGG

* C. D. Johnson, CERN/PS/90-42~AR.

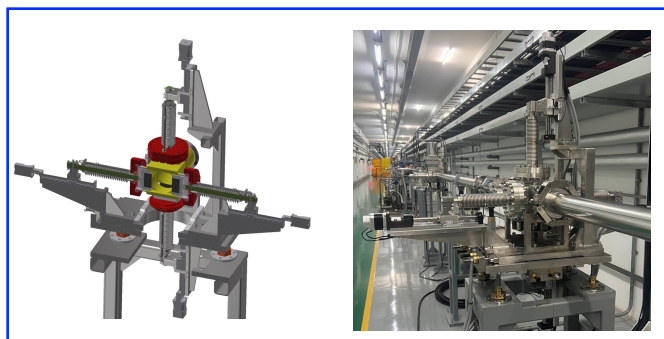
** J. Mukti, FNAL APC seminar (2013)

Conclusions

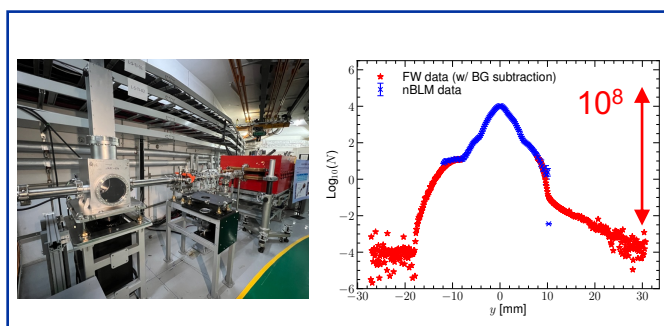
Multi-WS halo diagnostics



Carbon-foil collimators



Fluorescence wire scanner



- Halo diagnostics employing WS-nBLM scheme indicate a dynamic range of $>10^5$
 - Limited by the neutron/ γ -ray background in tunnel
 - A multi-WS halo monitor has been built
- A fluorescence wire scanner scheme has been proposed and demonstrated at CSNS LINAC
 - Chromox-6 wire was manufactured by waterjet-cutting
 - Combined with the core & tail measured by WS-nBLM, a max. dynamic range of $>10^8$ has been obtained
 - A new fluorescence material with a lower attenuation coefficient would be favoured

Thank you!

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Acknowledgements

T. Mitsuhashi (KEK)
T. Leferve (CERN)
S. Mazzoni (CERN)
P. Forck (GSI)
L. Ma (IHEP/CAS)
W. Huang (IHEP/CAS)

