The ANNI instrument

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arXiv:1811.11692

- Advantages of pulsed beams
- Guidelines of design
- Layout
- Performance

Proposers: *H. Abele* (TU Wien*), G. Konrad* (SMI Wien), *B. Märkisch* (TU München), *U. Schmidt* (Universität Heidelberg), *T. S.* (ILL), *C. Theroine* (ESS)

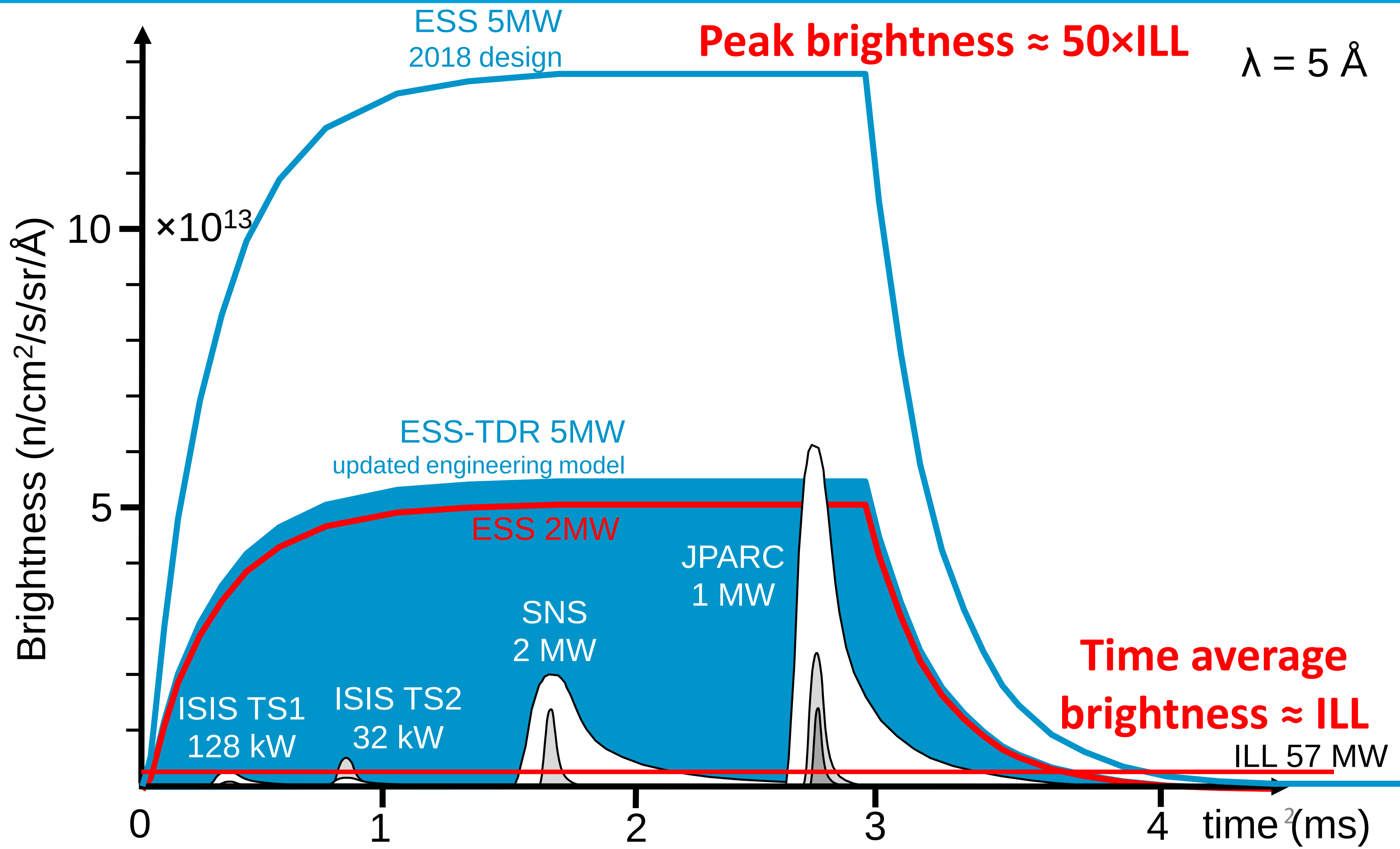
LOIs for experiments: *K. Bodek* (Jagiellonian University Krakow, n decay with BRAND), *F. Piegsa* (University of Bern, BeamEDM), *C. Crawford* (University of Kentucky, weak N-N interaction)

New partners very welcome!

adapted from: A. Schreyer, ESS (ILL-ESS user meeting, Oct. 2018)

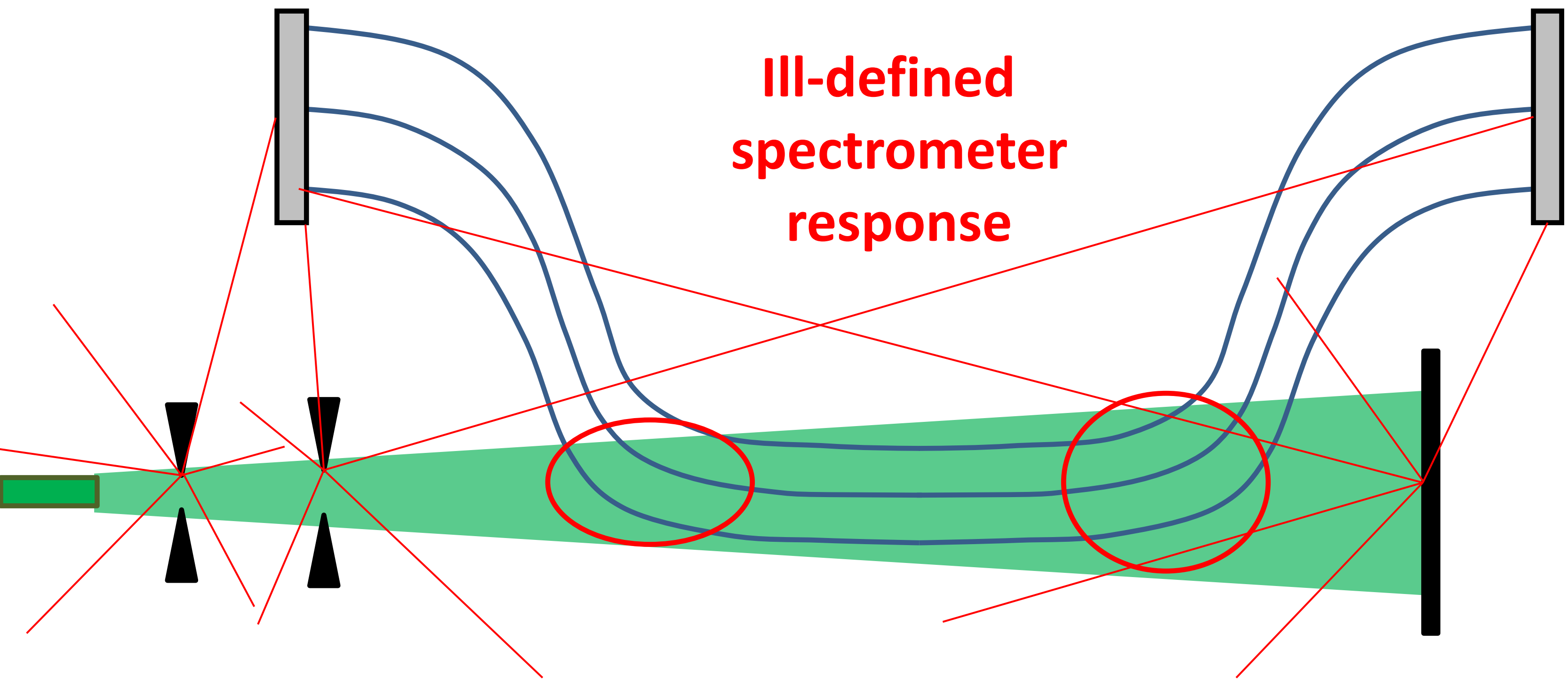
EUROPEAN SPALLATION SOURCE

Long-pulse performance



Advantage of pulsed beam – PERKEO III

Count rate (ILL): 40 000/s



Beam-related background

Scattering ~10^{-3}
γ, fast *n* ~10^{-4}

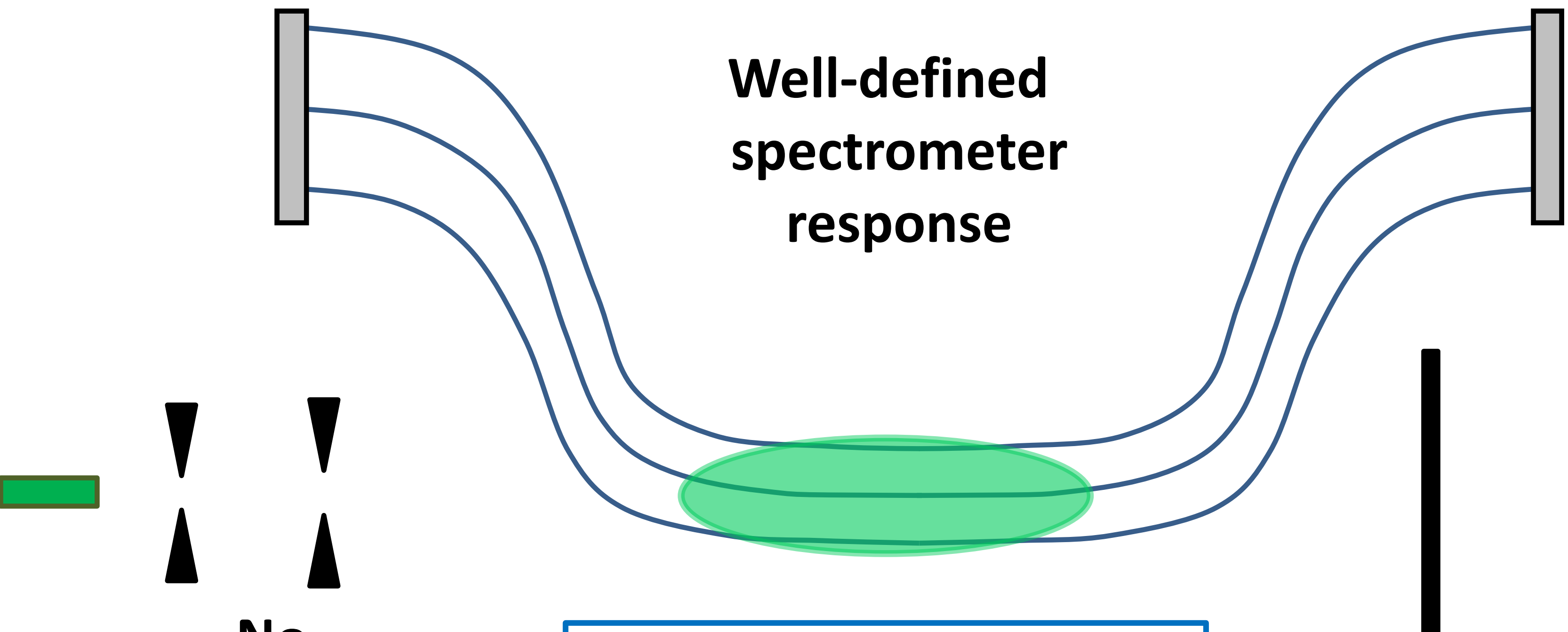
Decay probability ~ 10^{-6}/m
(Lifetime 880 s)

Spatial localization of neutrons

Usable count rate (ANNI): 3000/s

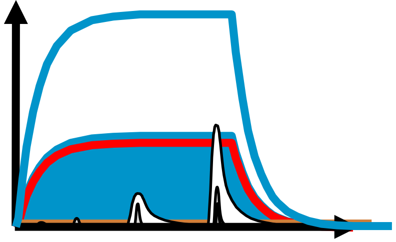
Usable count rate (ILL): 200/s

Monochromatization & chopping

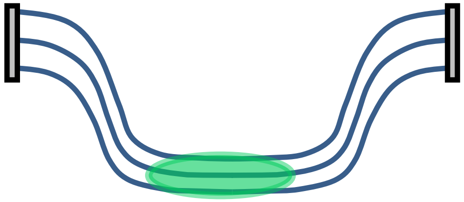


No beam-related background

Regain factor ~15 at pulsed source ESS!

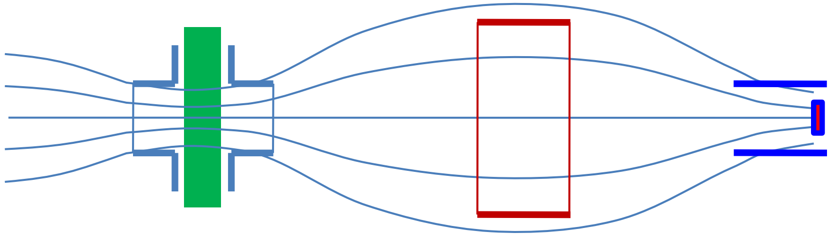


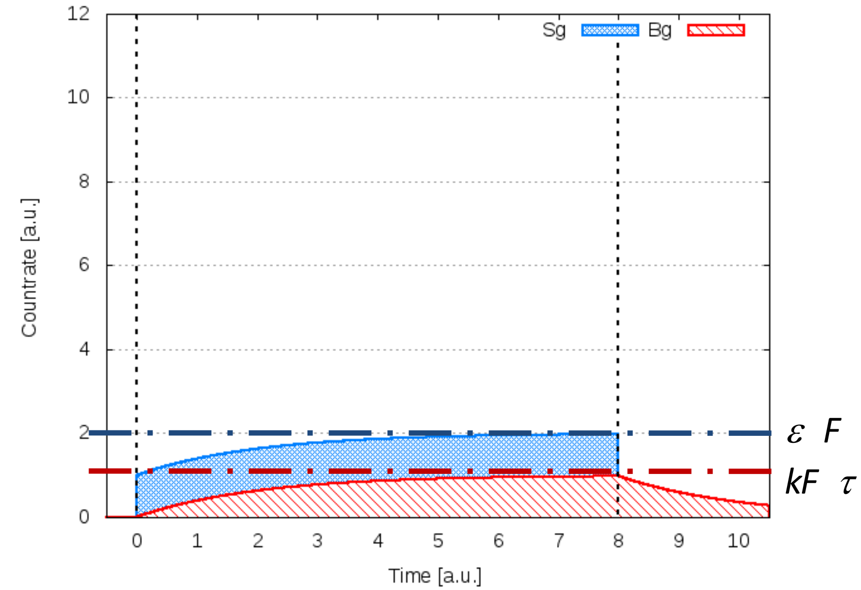
Pulsed beams provide...



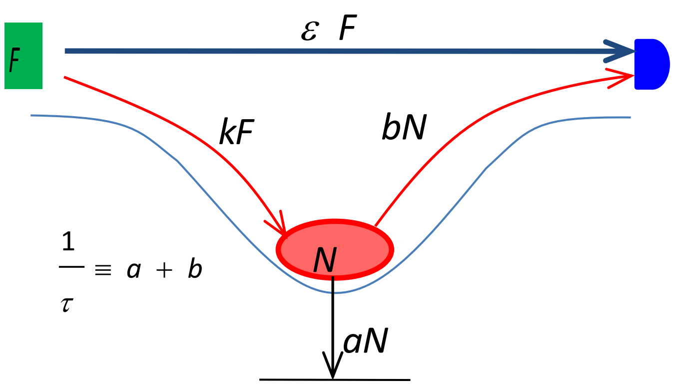
- Spatial localization of neutron pulse
  - Separation of beam-related background
  - Separation of undefined spectrometer response

Proton spectroscopy & traps





Compare R. Maisonobe: aSPECT background



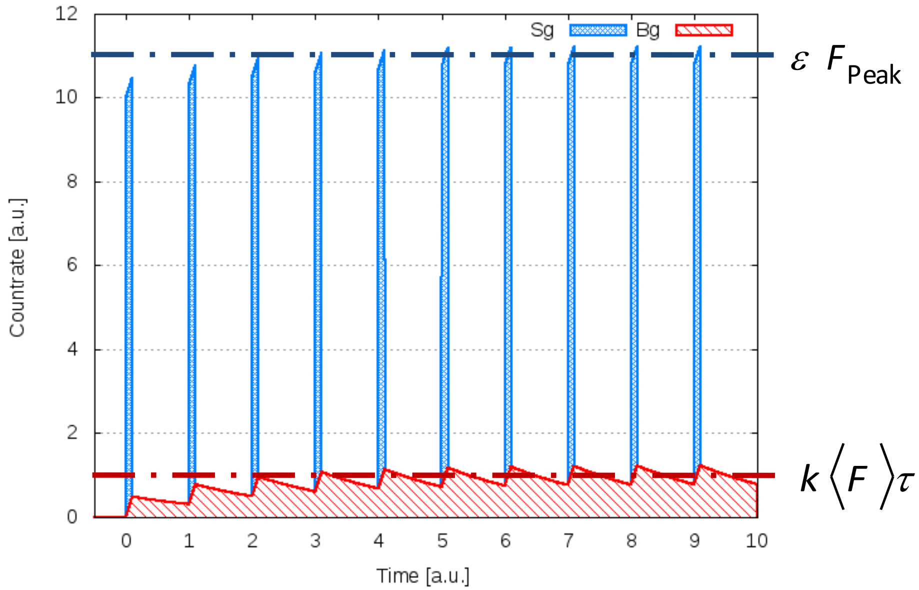
$$\frac{1}{\tau} \equiv a + b$$

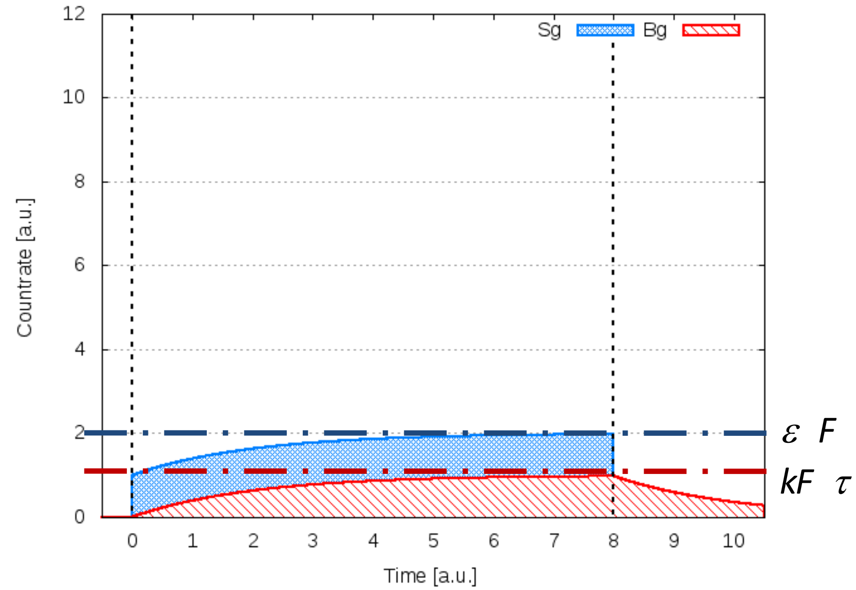
$$\frac{dN}{dt} = kF - \frac{N}{\tau}$$

$$\text{Beam ON}: \quad N(t) = \left(N_0 - kF\tau\right) e^{-\frac{t}{\tau}} + kF\tau$$

$$\text{Beam OFF}: \quad N(t) = N_0\, e^{-\frac{t}{\tau}}$$

Proton spectroscopy & traps





Pulsed beam:

$$\boxed{\left(\frac{\mathrm{Sg}}{\mathrm{Bg}}\right)_{\mathrm{Pulsed}} = \frac{F_{\mathrm{peak}}}{\langle F\rangle}\left(\frac{\mathrm{Sg}}{\mathrm{Bg}}\right)_{\mathrm{Cont}}}$$

$$\text{Beam ON}: N(t) = (N_0 - kF\tau)\, e^{-\frac{t}{\tau}} + kF\tau$$

$$\text{Beam OFF}: N(t) = N_0\, e^{-\frac{t}{\tau}}$$

Localization in time

BG with different time constant

- Traps of charged particles
- Background from beta activation

BG time constant ≫ Pulse period

Gain:

$$\left(\frac{Sg}{Bg}\right)_{Pulsed} = \frac{F_{peak}}{\langle F \rangle}\left(\frac{Sg}{Bg}\right)_{Cont}$$

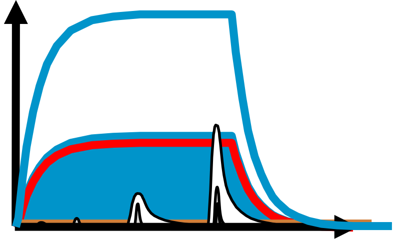
Changing environment

- Variable background conditions (neighbors, high voltage)
- Drifting detector

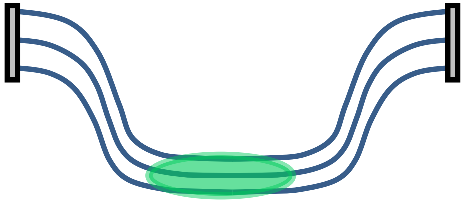
Typical drift times ≫pulse period

Gain:

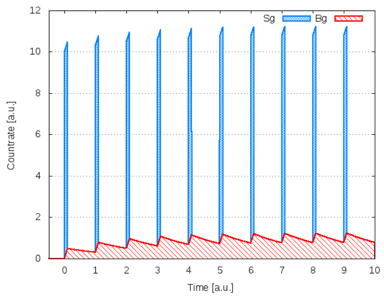
- Measure parameters close to signal and correct



Pulsed beams provide...

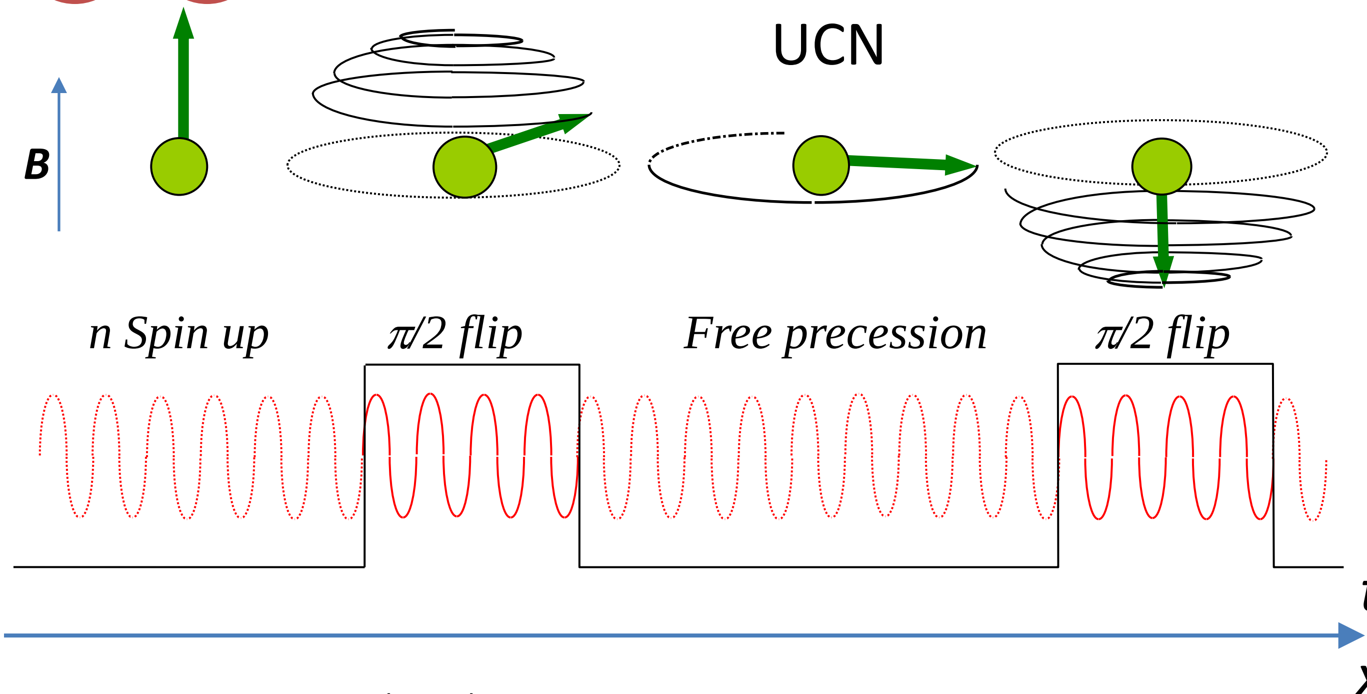


ξ Spatial localization of neutron pulse
- Separation of beam-related background
- Separation of undefined spectrometer response



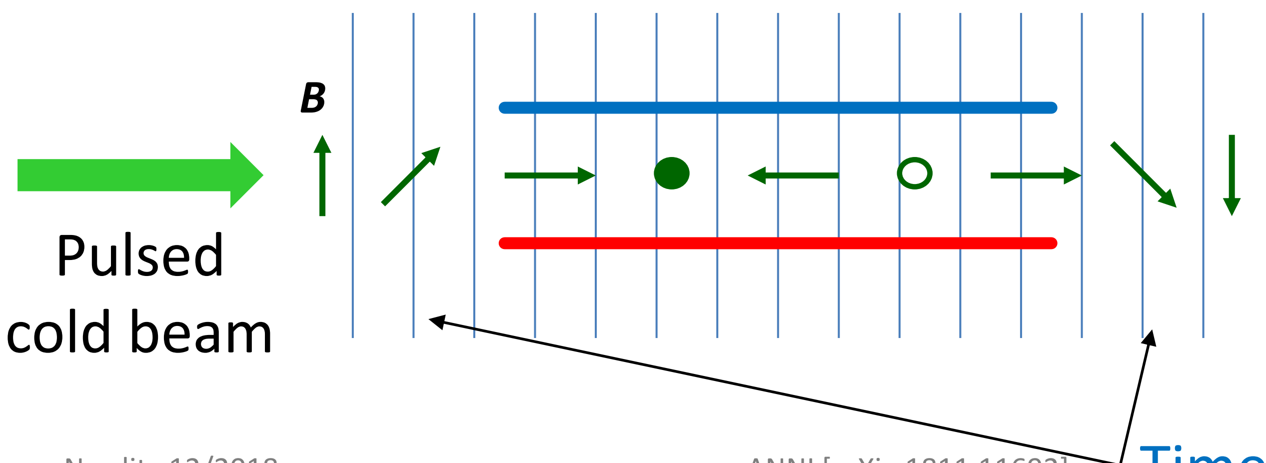
τ Time localization of neutron pulse
- Signal/background
- Suppression of background and drifts with different time constan

Electric dipole moment

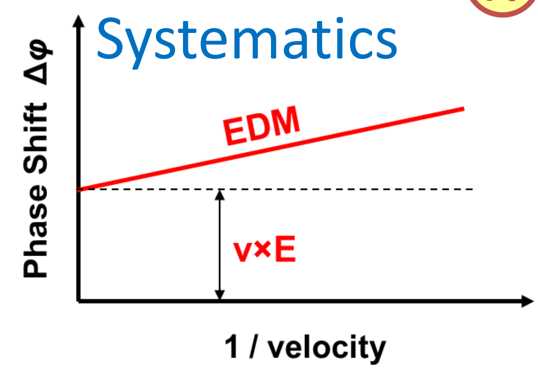


$$\boxed{\sigma_d \propto \frac{1}{E\,T\sqrt{N}}}$$

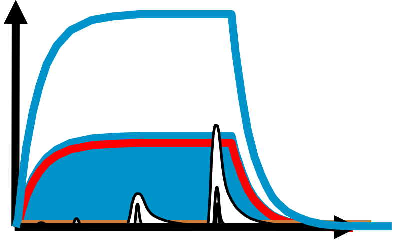
Piegsa, *PRC* 88, 045502 (2013)



v-dependent
Systematics

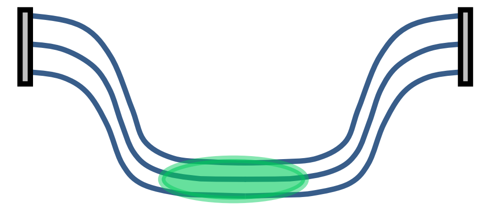


Time-dependent optics



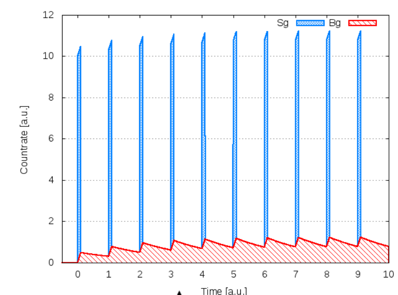
Pulsed beams are good for you!

ξ Spatial localization of neutron pulse



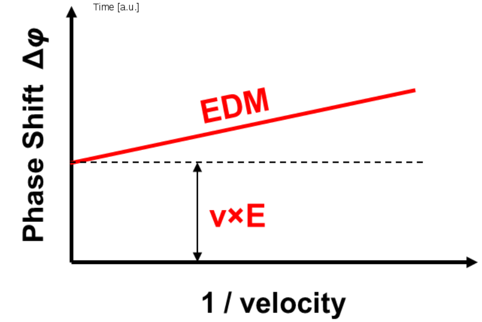
- Separation of beam-related background
- Separation of undefined spectrometer response

τ Time localization of neutron pulse



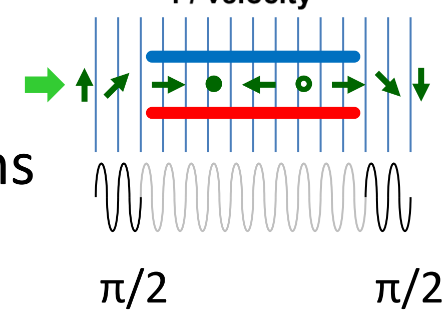
- Signal/background
- Suppression of background and drifts with different time constant

λ Separation by neutron wavelength



- Velocity dependence of signal and systematics
- Loss-free monochromatization

↖ Time-dependent neutron optics



- Wavelength-specific optics adapts to all neutrons

ANNI – Science case

- Neutron beta decay with 10^{-4} accuracy — Thursday
  - Broad-band probe for physics beyond the standard model, at scales of 1-100 TeV
- New approaches to electromagnetic properties of the neutron — Monday afternoon
  - Beam methods for EDM and charge as probe for matter creation and unification of forces
- Absolute measurements in hadronic weak interaction — Tuesday afternoon
  - Systematic experimental study of QCD in non-perturbative regime

\+ Other applications — HIBEAM next talk
  - Nuclear physics, R&D (HIBEAM?)...

ANNI – Concept

Maximum statistics at minimum systematics
for versatile user instrumentation

→Fully exploit pulse structure

→Assure low background

→Optimize for beam quality

→Include polarization

→Include ep/n separator

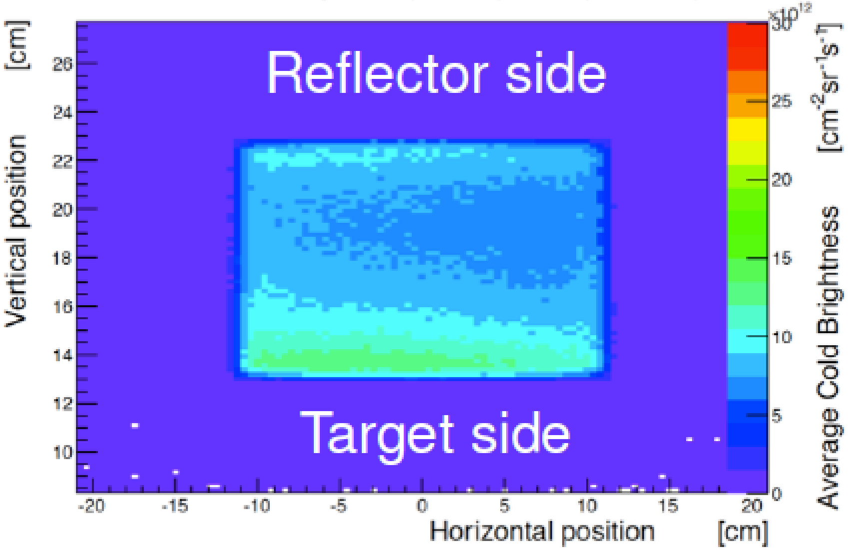
→Provide flexibility

→ Short instrument

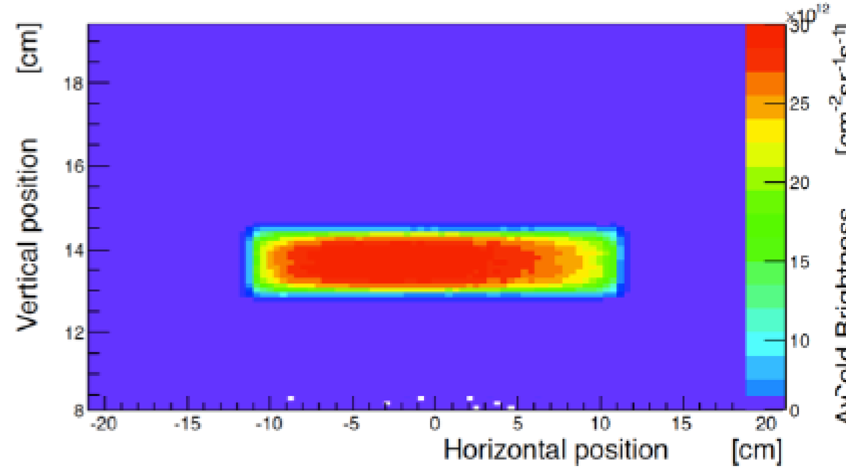
14 Hz ESS, no frame overlap, optimization for pulse localization → experiments start at 26 m

ESS cold moderator

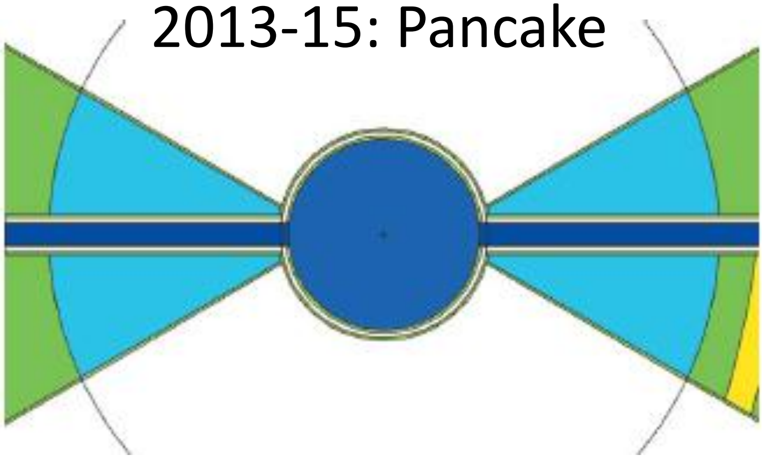
TDR: Volume



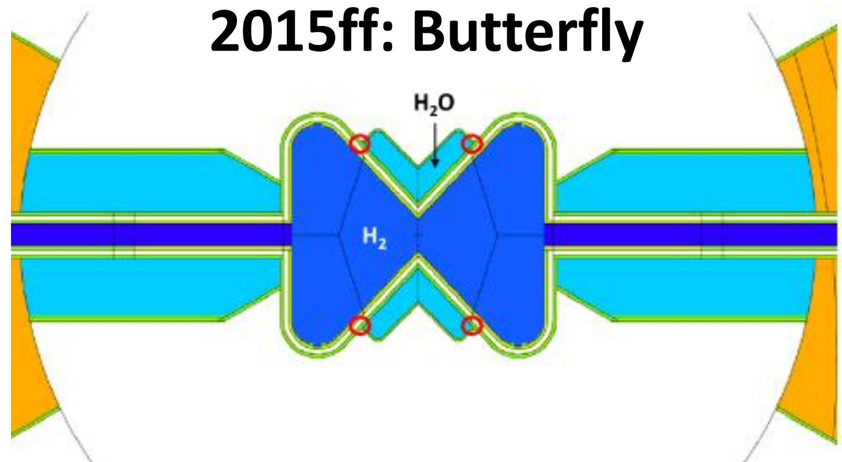
2013ff: Low-dimensional



2013-15: Pancake



2015ff: Butterfly



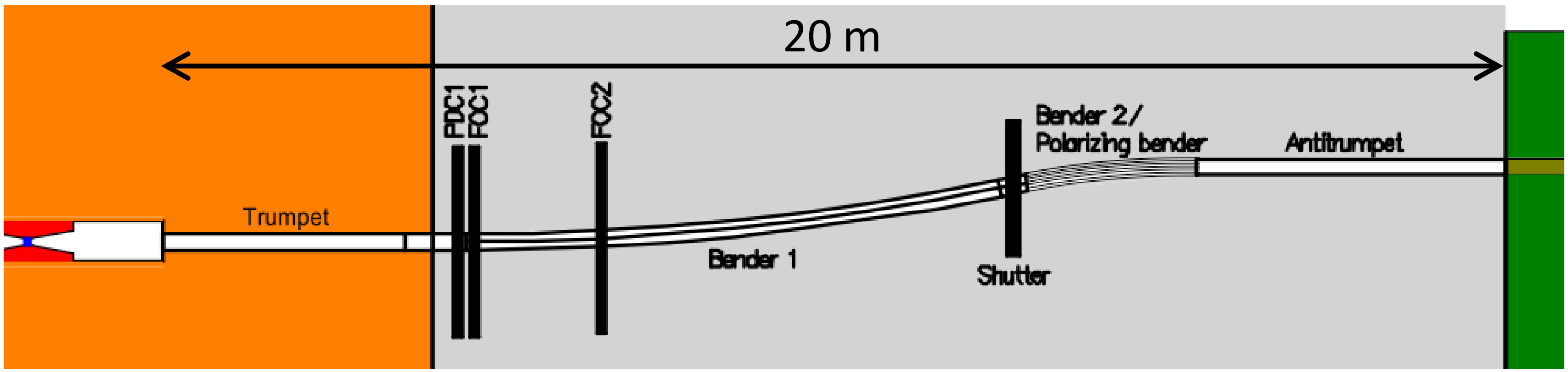
From talks by ESS moderator group and K. H. Andersen et al., J. Appl. Cryst. **51**, 264 (2018)

ANNI – Guide concept

Short guide

2 × out of sight → Strong curvature

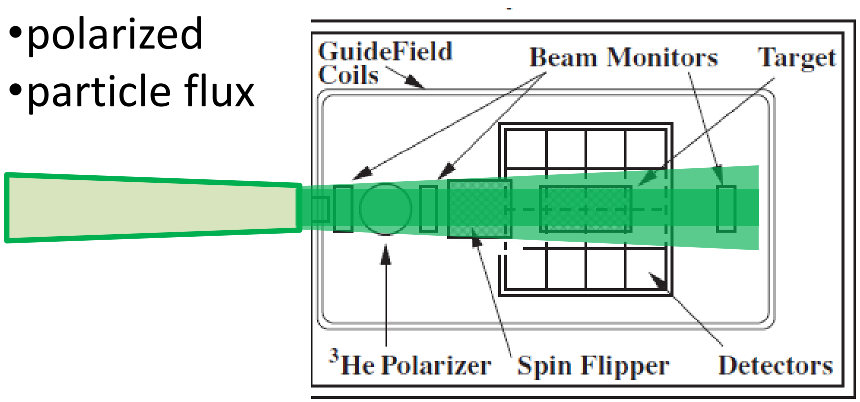
Benders



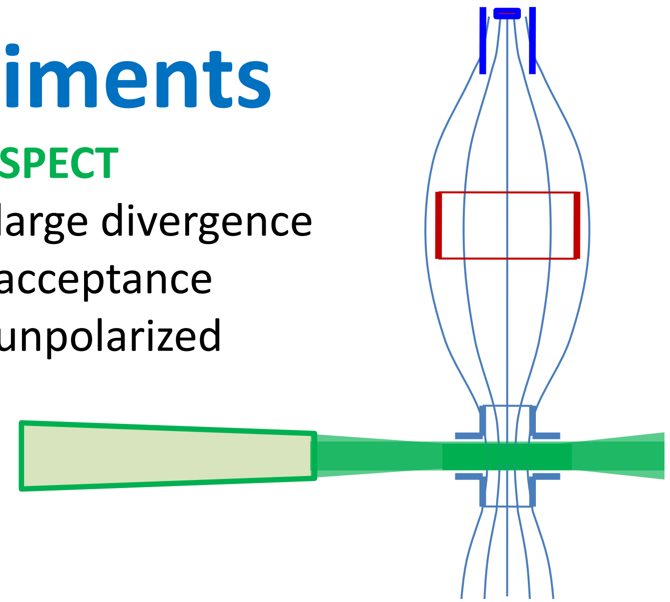
Element	Dist [m]	Radius [m]	Length [m]	Cross-section [cm²]	#	*m* value	*γ** [mrad]	*λ** [Å]
Trumpet	2.0	∞	3.6	9×6→*13×6*	1	3.5 / 3.0		
Straight 1	5.6	∞	0.9	13×6	1	3.0		
Bender 1	6.5	270	8.0	13×6	2	3.0, B: 3.5	14.7	2.44
Straight 2	14.5	∞	0.4	13×6	2	3.0		
Bender 2 / Pol	14.9	–84	2.5	13×6	6	3.0, T: 3.5	14.7	2.44
Anti-trumpet	17.4	∞	4.6	13×6→*11×7*	1	3.5 / 3.0		

Reference experiments

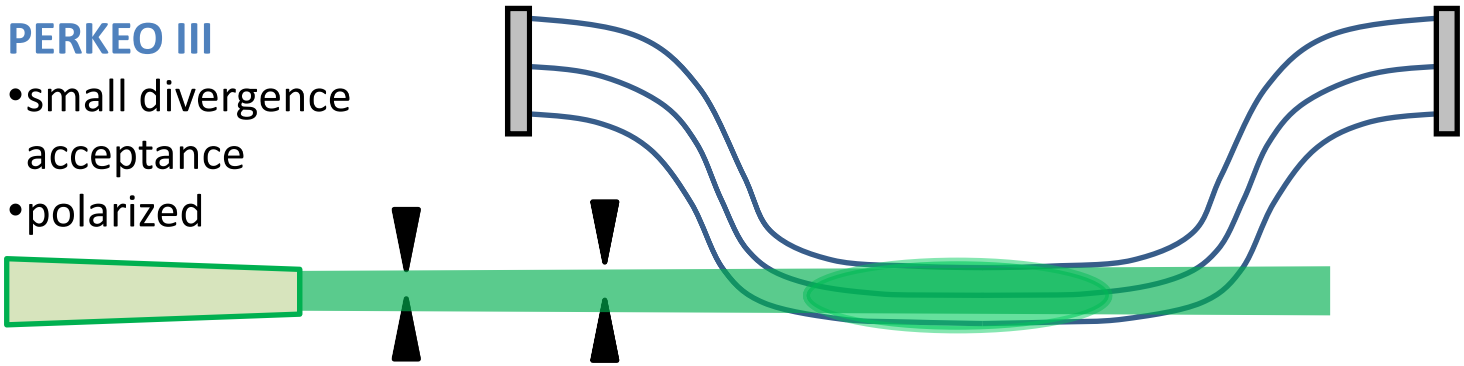
NPDGamma
- large divergence acceptance & beam area
- polarized
- particle flux



aSPECT
- large divergence acceptance
- unpolarized



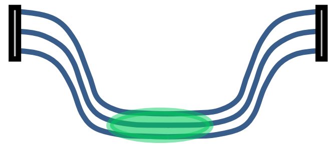
PERKEO III
- small divergence acceptance
- polarized



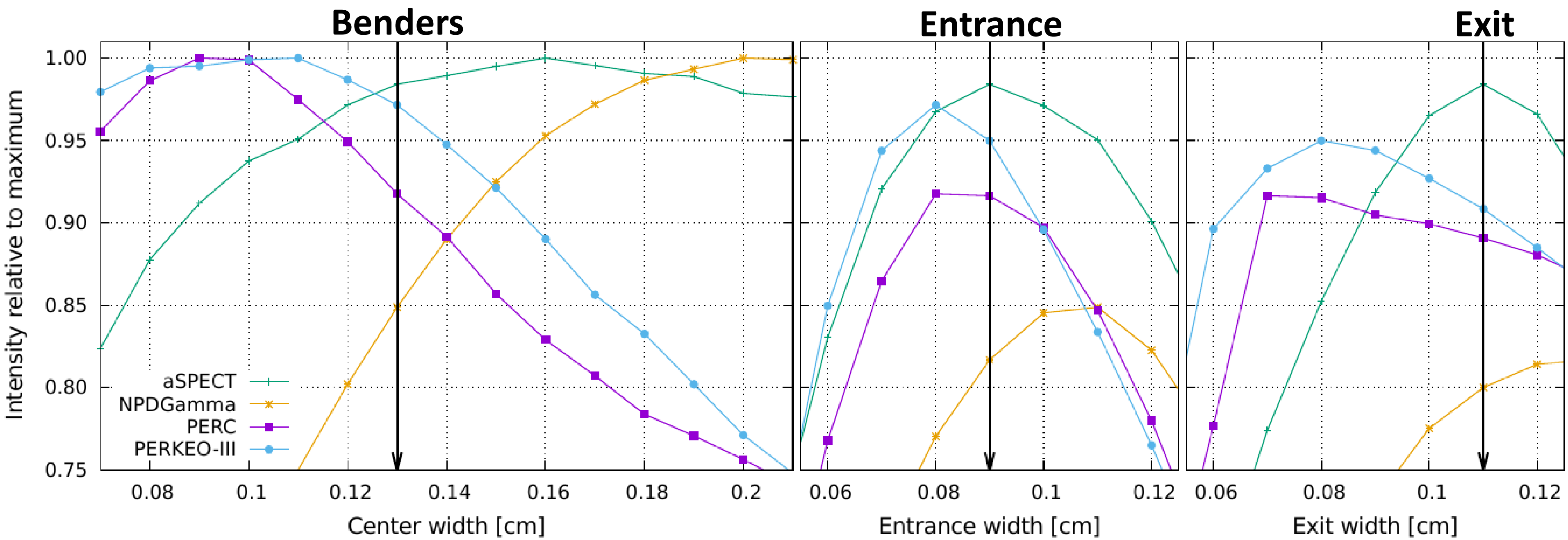
PERC
- Decay volume in neutron guide
- polarized

Example: Optimization in horizontal plane

Butterfly



Reference exps

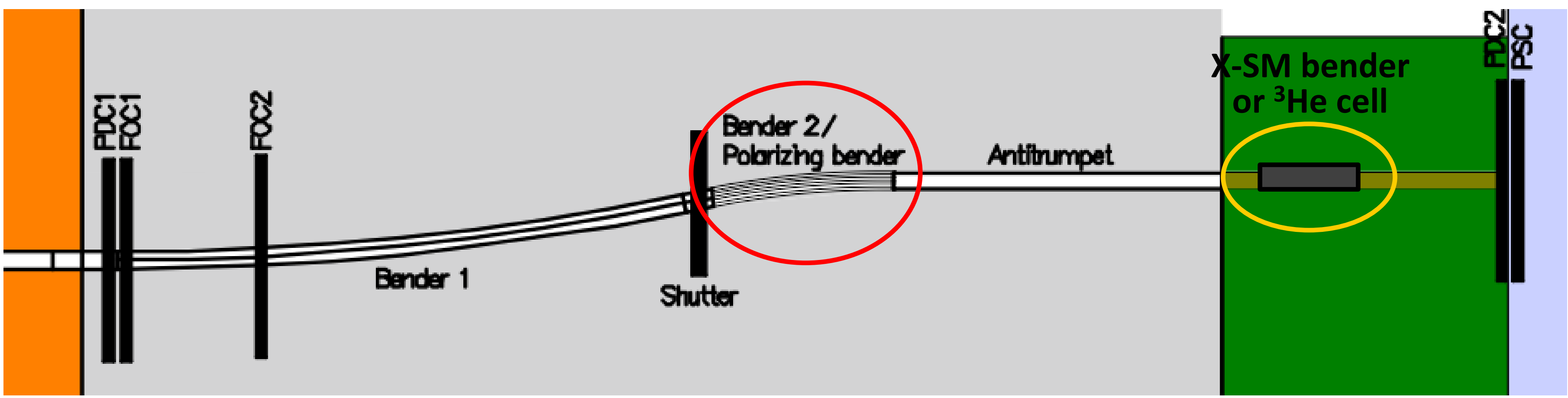


Design is "best" compromise ← Priorities, guessed developments…

Still 80% of maximum performance for each reference experiment

ANNI – Polarization options

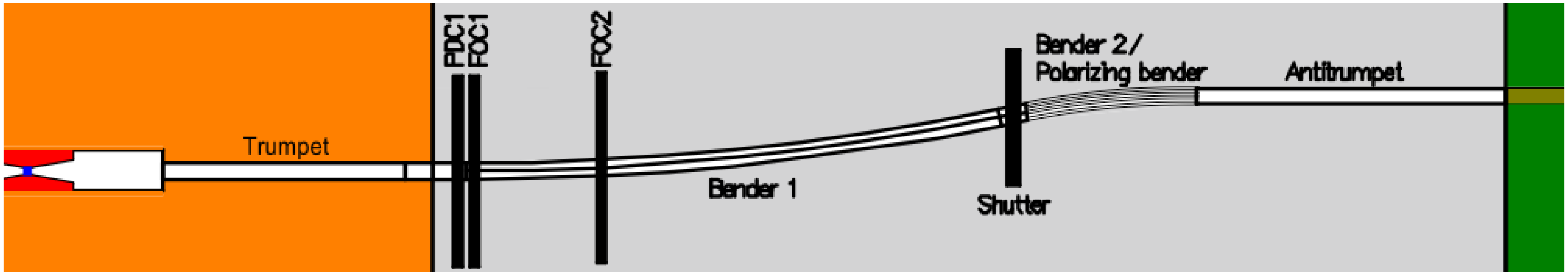
- **Moderate polarization at highest intensity**
  Bender 2 → Polarizing bender
- **Highest polarization**
  Polarizing bender + bender in beam preparation area in X-SM geometry
- **Polarization with analytic wavelength dependence**
  ^{3}He spin filter in beam preparation area



ANNI – Chopper system

Goal: fully exploit pulse structure

→ Frame overlap suppression, pulse localization in space and time, pulse multiplication, monochromatization

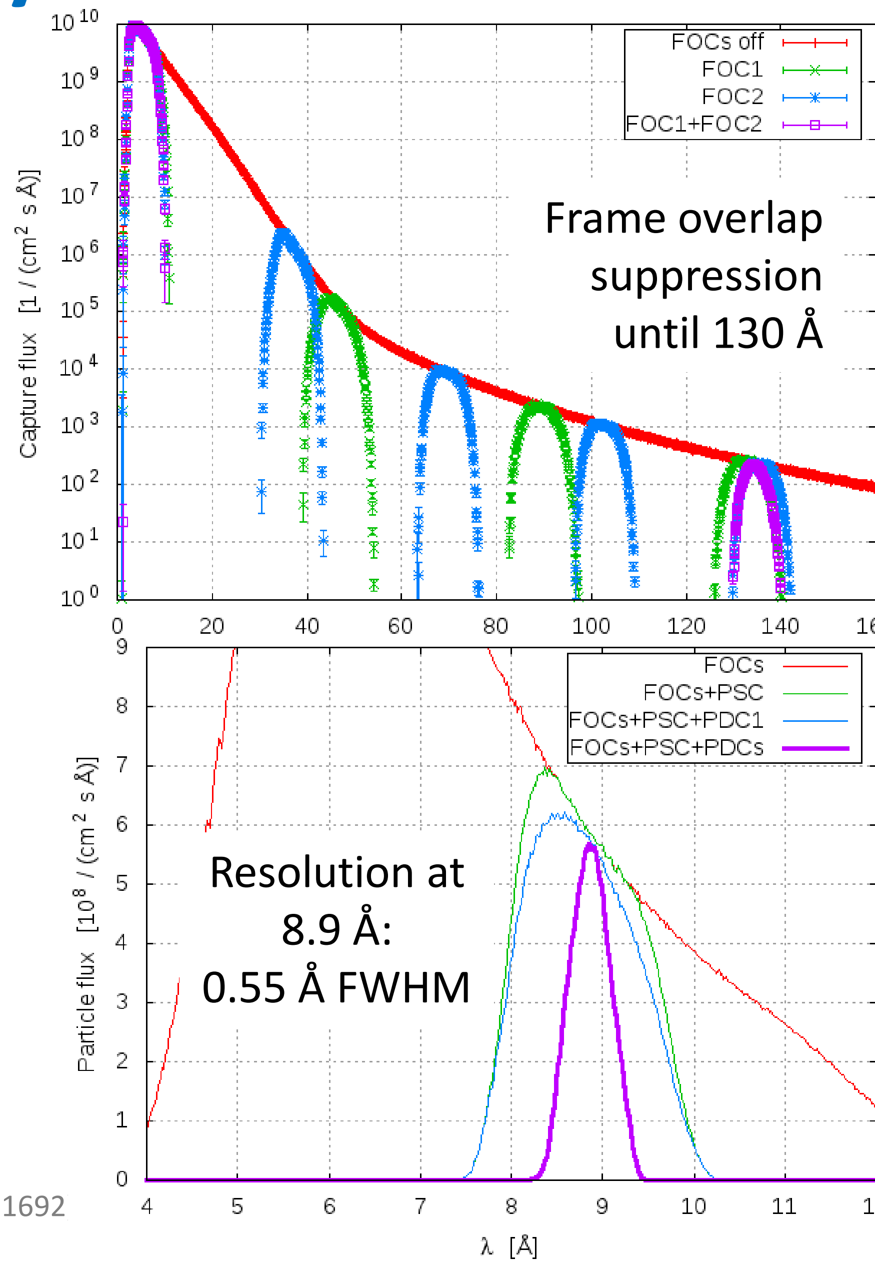


	Dist [m]	Radius [cm]	Frequency [Hz]	Angle [º]	Comment
PDC1	6.5	40	14—70	Variable	2 counter-rot pairs of co-rot disks
FOC1	6.5	40	14	64	Single disk
FOC2	8.5	40	14	79	Single disk
PDC2	26	40	14—70	Variable	2 counter-rot pairs of co-rot disks
PSC	26	40	14	60	Single disk
PMC	26	40	14	Multi-slit	2 counter-rotating disks, replacing the disks of the PDC2

ANNI – Chopper system modes

- **Full intensity:** Choppers off
- **Maximum intensity without frame overlap:** Only FOCs
- **Time localization:** PDC2 large opening + FOCs
- **Monochromatic:** PDCs small opening @ 70 Hz + FOCs
- **Spatial localization:** PDCs small opening @ 70 Hz or pulse multiplication + FOCs

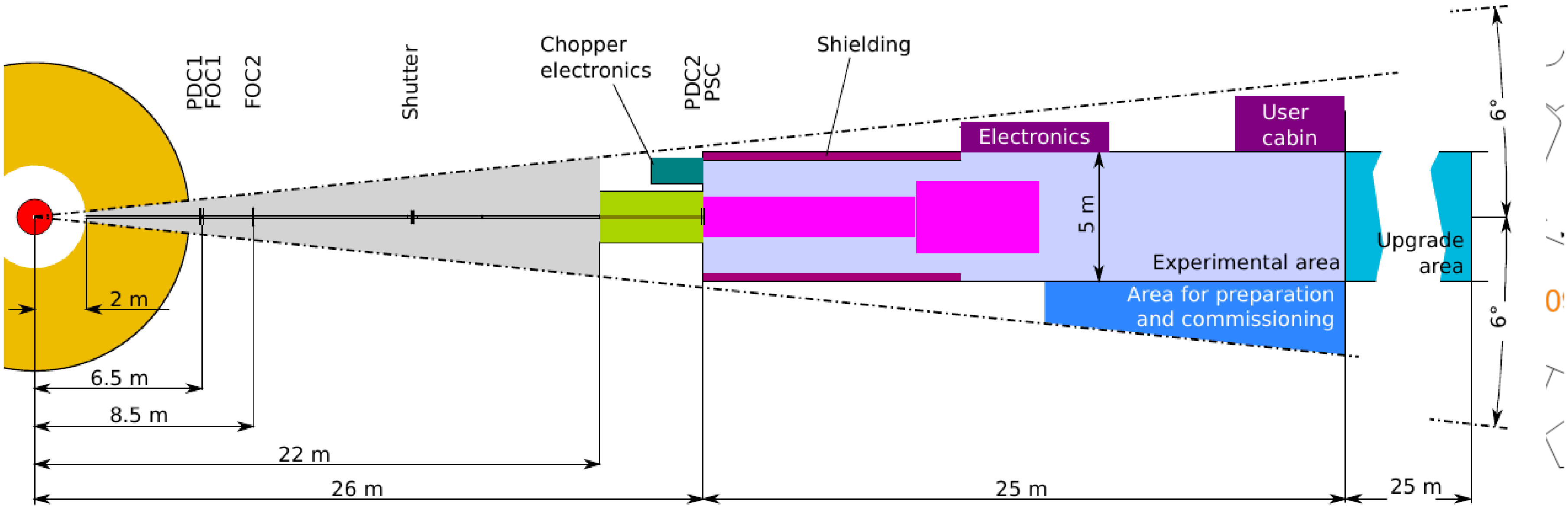
Pablo Torres-Sánchez, ILL internship report → pulse multiplication not attractive for PERKEO III



ANNI [arXiv:1811.11692

ANNI – Floor plan

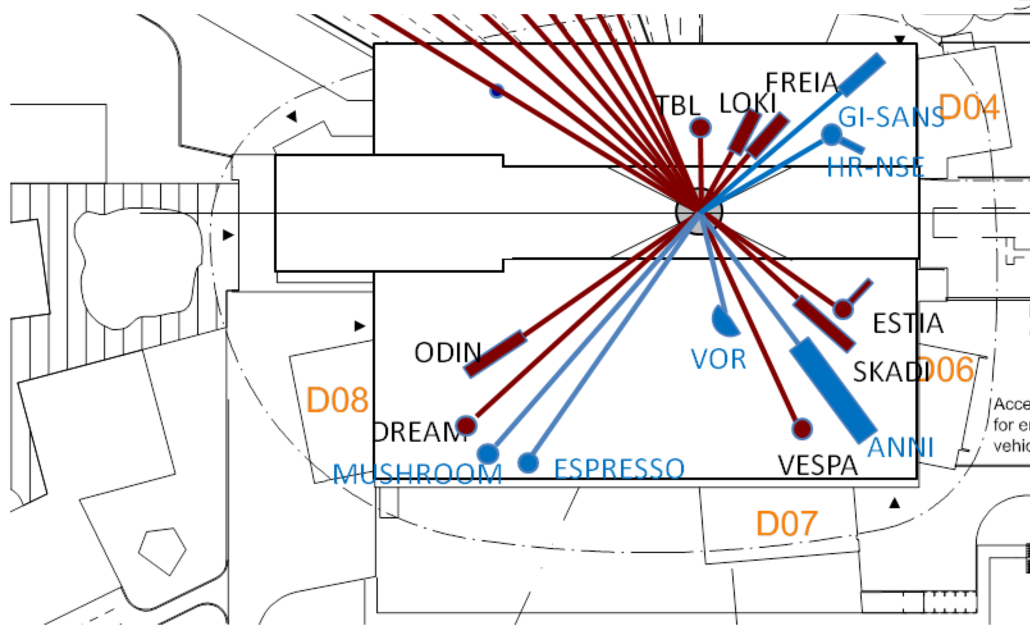
arXiv:1811.11692



Possible placement at ESS:

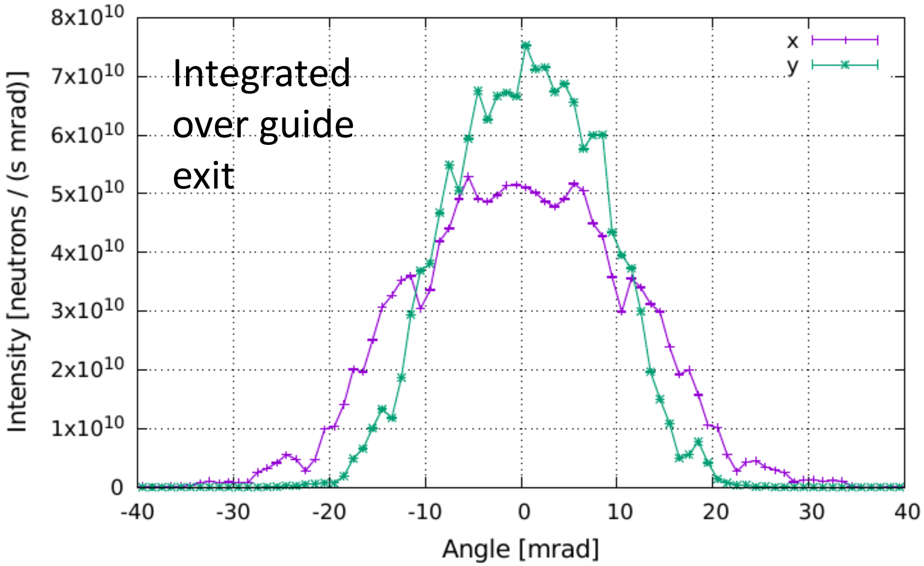
Beam port E5

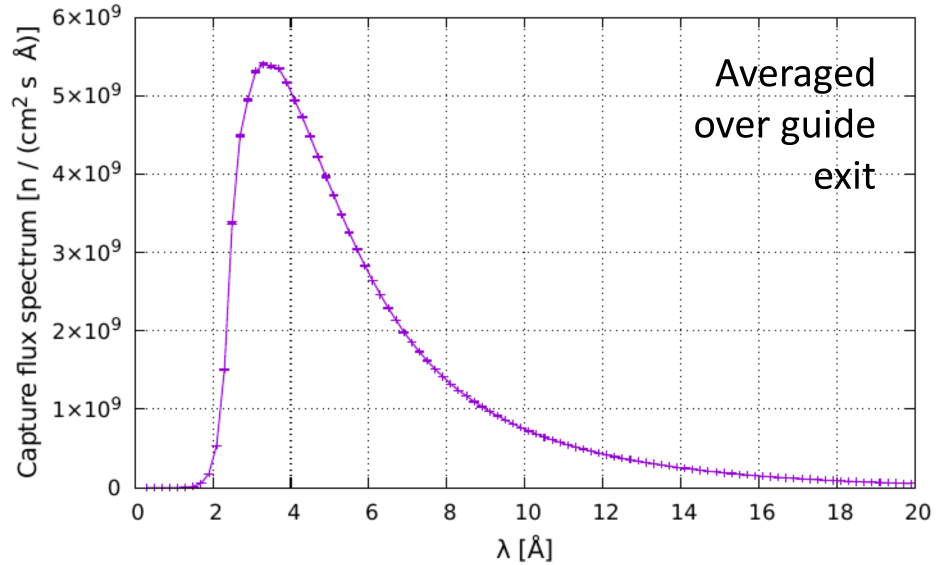
[K. Andersen, Report ESS-0080327 (2016), A. Schreyer, ESS (ILL-ESS user meeting, Oct. 2018)]



ANNI – Performance @ 5MW

arXiv:1811.11692





Capture flux density full spectrum: 2.5×10^{10} n/cm^{2}s

Capture flux density 2-8 Å: 2.0×10^{10} n/cm^{2}s

Particle flux density @ 8.9 Å: 2.1×10^{8} n/cm^{2}sÅ

(Averaged over guide exit area 11×7 cm^2)

ANNI – Benchmarks @ 5MW

arXiv:1811.11692

Experiment	Facility	Gain Event rate	Comment
NPDGamma	FnPB (SNS 1.4 MW)	**15**	Wavelength information
PERC	MEPHISTO (FRM II)	**15**	Pulse localization in space
PERKEO III	PF1B (ILL)	**17**	Pulse localization in space
aSPECT	PF1B (ILL)	1.3 2.8	Full spectrum Pulse localization in time to 1/3 of T_{ESS}
BeamEDM	PF1B (ILL)	**>25**	Wavelength information, time dependent optical elements

World leading from 1 MW ESS power

Summary

ANNI: Cold beam facility for manifold applications

arXiv:1811.11692

- Fully exploits ESS pulse structure
  - Pulse localization in space and time
  - Wavelength-dependent systematics
  - Time-dependent neutron optics

ξ τ λ ↖

→Cleaner systematics at full statistics

- Design optimized for reference experiments
- Will outperform all existing cold beam lines for particle physics by >1 order of magnitude