The Beam Delivery System of the European Spallation Source

Heine Dølrath Thomsen
ISA, Dept. of Physics and Astronomy
Aarhus University, Denmark
(on behalf of all the ESS raster system contributors)

57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams
Malmö, Sweden, 3-8 July 2016


European Spallation Source
2019
Malmö
CPH
Lund
Science Village
MAX IV
Target, moderators
Neutron instruments
Pulsed linac
2.86 ms
2.86 ms
1 / 14 Hz
H+
5 MW beam power
95% availability

Accelerator-to-Target (A2T) @ High-Power?

- "Uniform" beam spot
  - To prolong lifetimes of target vessel and proton beam window (radiation damage); cooling;

- Proton beam windows
  - Lifetime due to irradiation, cooling problem, multiple scattering effect

- Back-streaming neutrons
  - Very high flux, damage to devices in the beam transport line; radiation shielding burden

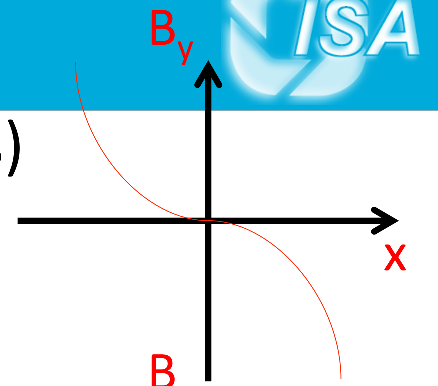
- Beam monitoring
  - Monitoring beam centering and profile at target; lifetime and shielding of probes in a radiation-hard region

Uniform Beam Spot?

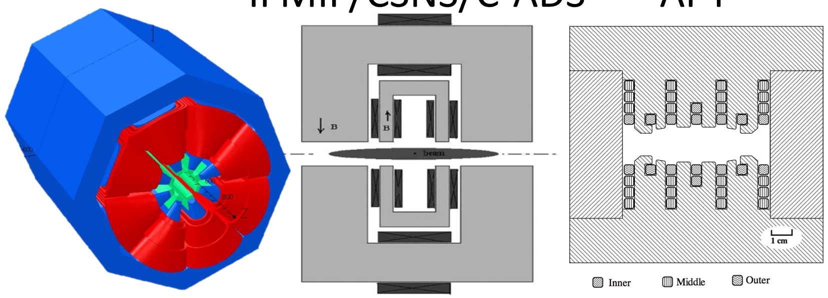
Lin. expansion + (quadrupoles)

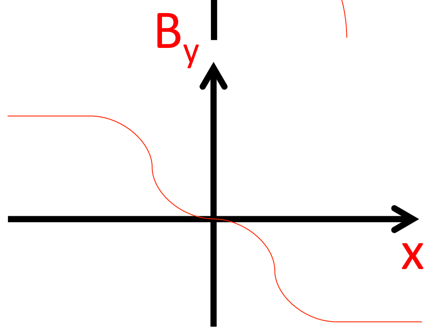
(LANL APT), (ESS-2003), BNL NSRL, J-PARC, CSNS, C-ADS, IFMIF, …

- Non-Linear Magnets (NLMs)
  - Multipoles 6, 8, 12, …
  - Combined function



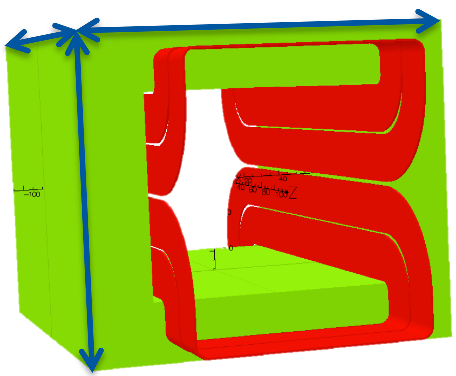
IFMIF/CSNS/C-ADS APT

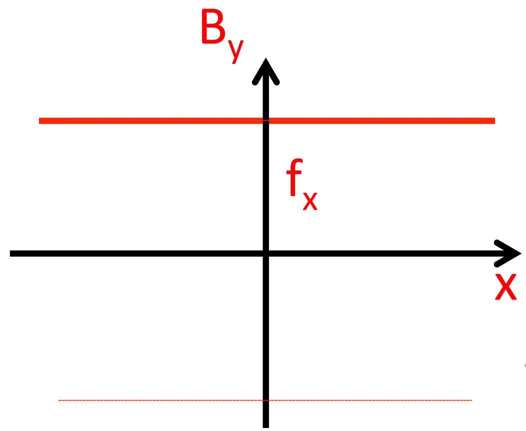




CEBAF, (LANL APT), LANL MTS, MYRRHA, SINQ, …

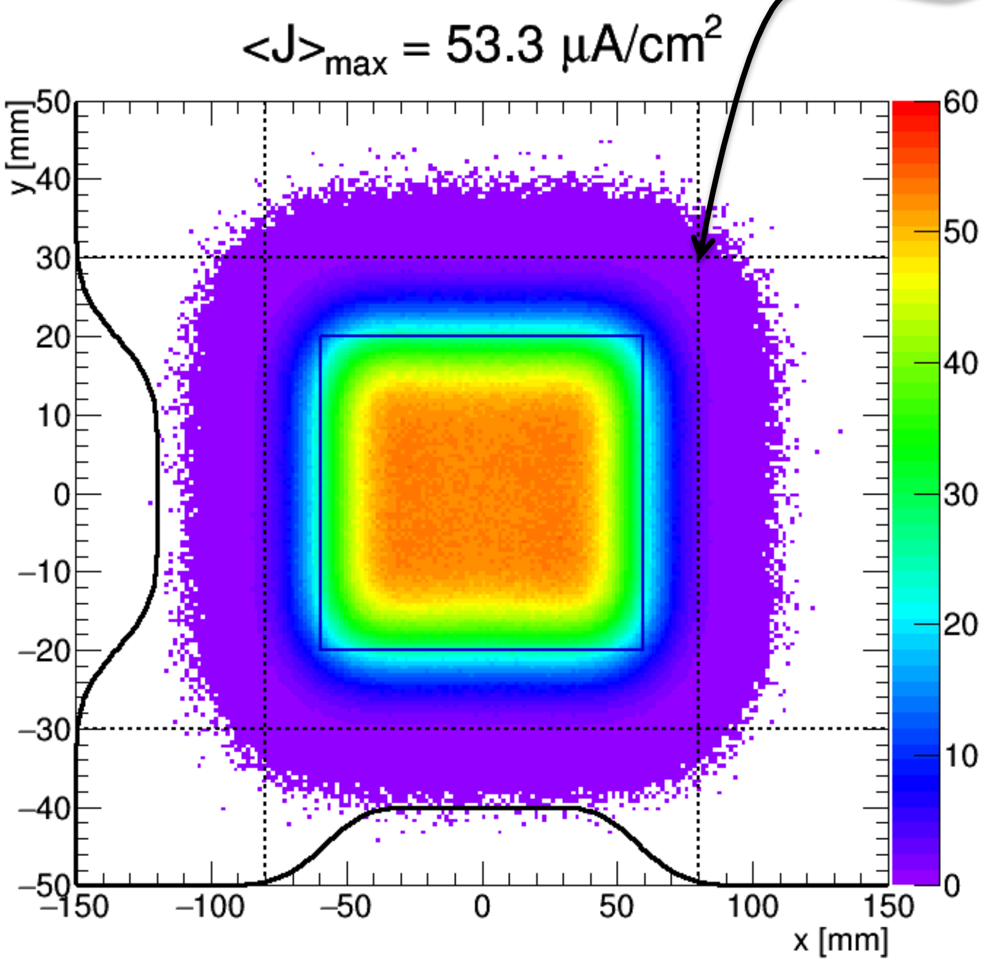
- Raster Scanning Magnets (RSMs)
  - Convolution of AC and DC beam optics





ESS Requirements: Beam

Figures of merit:
- Peak current density (J_{max}) on target
- Beam inside nominal footprint regions (>99%, >99.9%)



Example distribution, 3:1 H-V aspect ratio

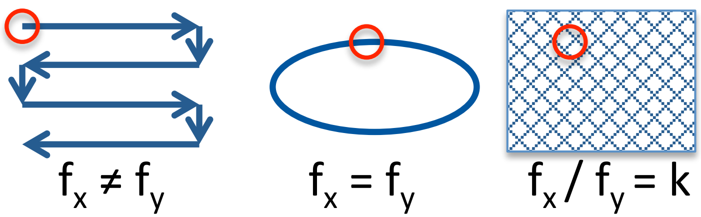
	Unit	Target surface
<Jmax>, nominal	uA/cm^2	56
<Jmax>, max.	uA/cm^2	71
***p* outside 160x60**	%	<1
***p* outside 180x64**	%	<0.1
Max. avg. pulse displacement	mm	± 5 (H) ±3 (V)

- Primary beam losses near target should be minimized as much as reasonably possible!
  - 70% of ESS *n* instruments will be very sensitive to this!
  - (HYSPEC@SNS+AMATERAS@J-PARC)

Expander Systems Considered for ESS

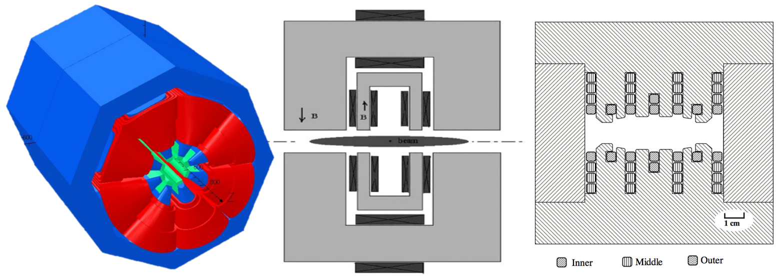
Raster Scanning Magnets (AC)

- Introduces a time structure
- Suitable for CW or long-pulse machines
- Raster pattern ⊗ DC beamlet
- Simple tuning
  - Beamlet and pattern: decoupled!
  - DC beamlet profile is suppressed

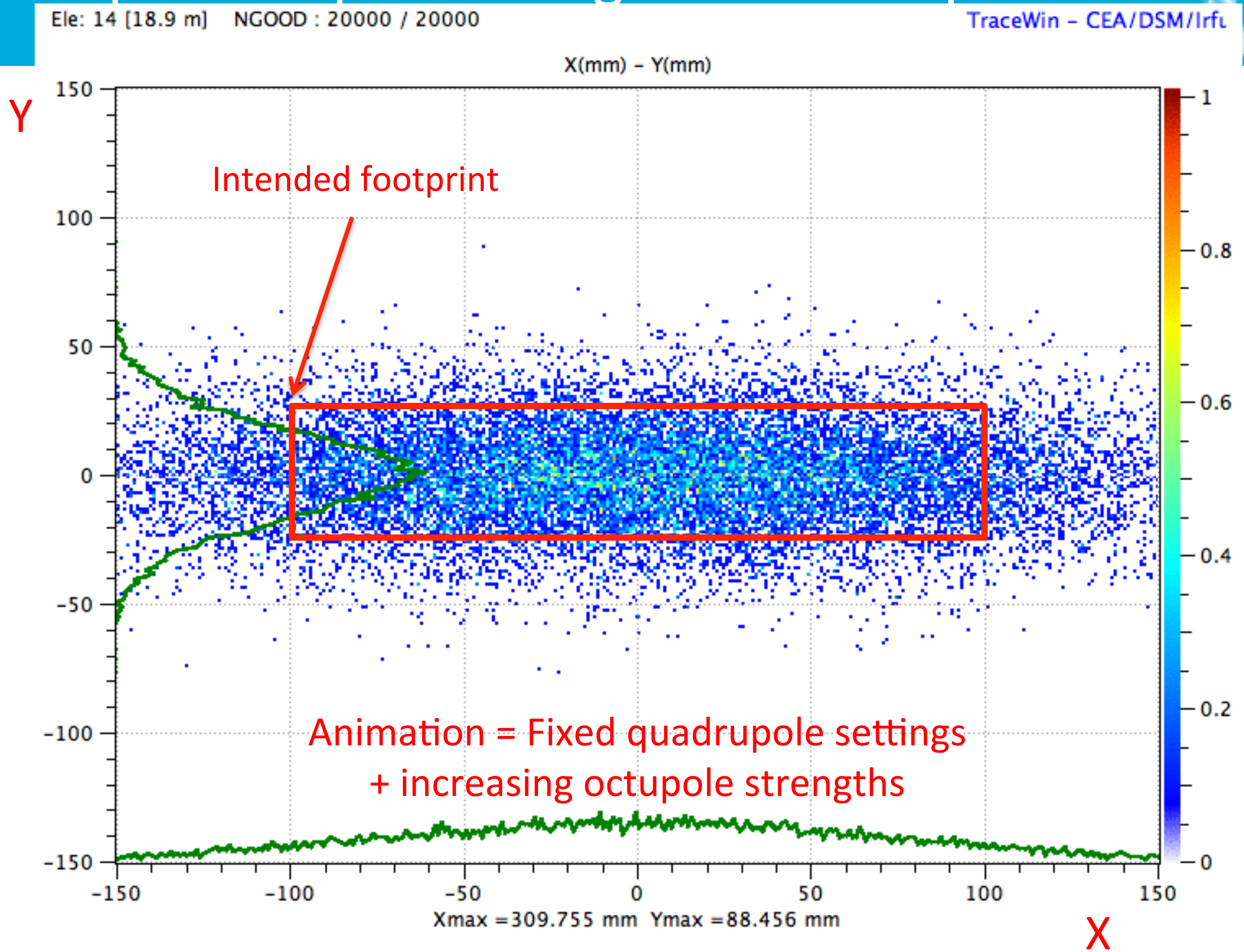


Non-Linear Magnets (DC)

- NLM field distorts phase space – focuses tails
- Uniform beams can be tailored…
  - If the input beam is well-known
  - If "large" relative beam losses are acceptable
- Potential problems
  - H-V Coupling
  - Overfocusing of halo (octupoles)

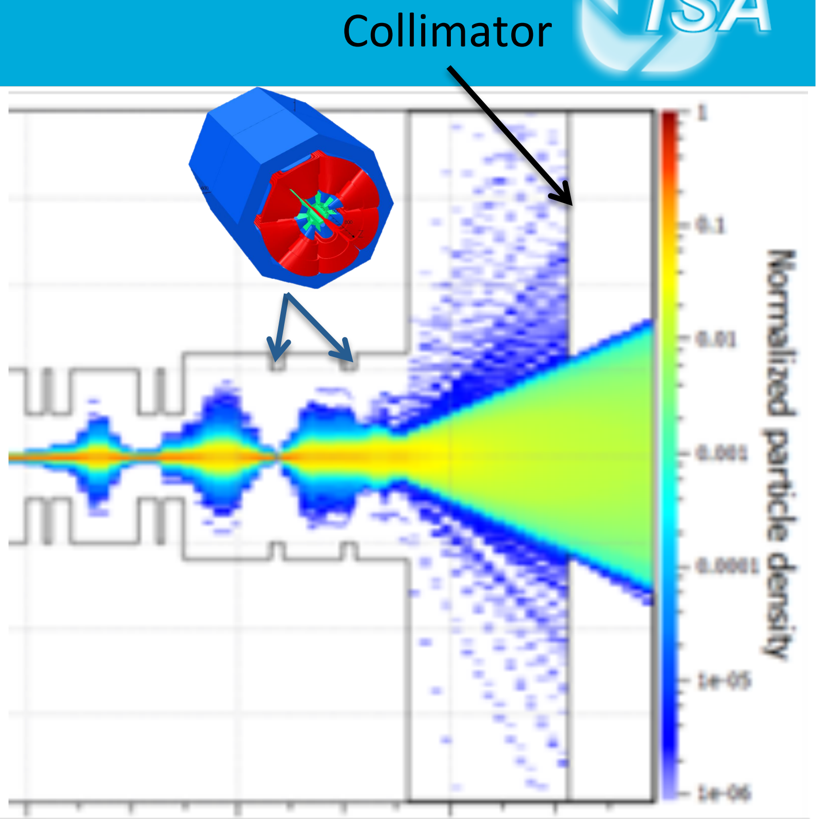


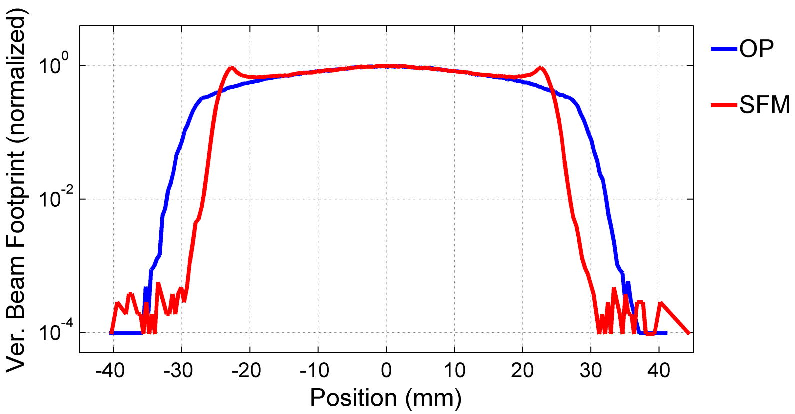
Example Footprint using H & V Octupoles

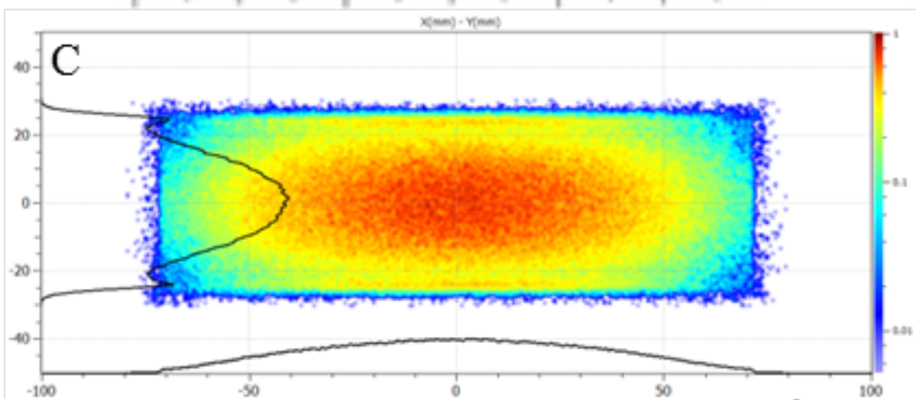


ESS Studies of NLMs: Octupoles & SFMs

- Several papers about tuning
  - "Expert operator"
- Sensitive towards beam distribution
- $10^{-4} - 10^{-3}$ (5 kW) intercepted by collimator upstream of target
  - Source of *n* backgrounds!







A. Holm *et al.*, IPAC'12, MOPPD049

LANL APT: (1990's)

ESS:
- Pulsed, no cooling necessary
- Requirement: f_x > 35 kHz (*n* pulse)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 039001 (2008)

Comment on "Uniformization of the transverse beam profile by means of nonlinear focusing method"

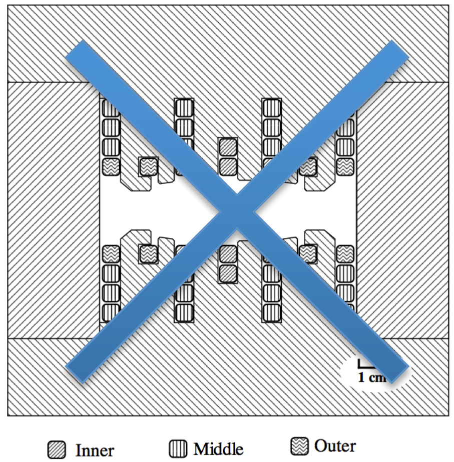
Robert E. Shafer

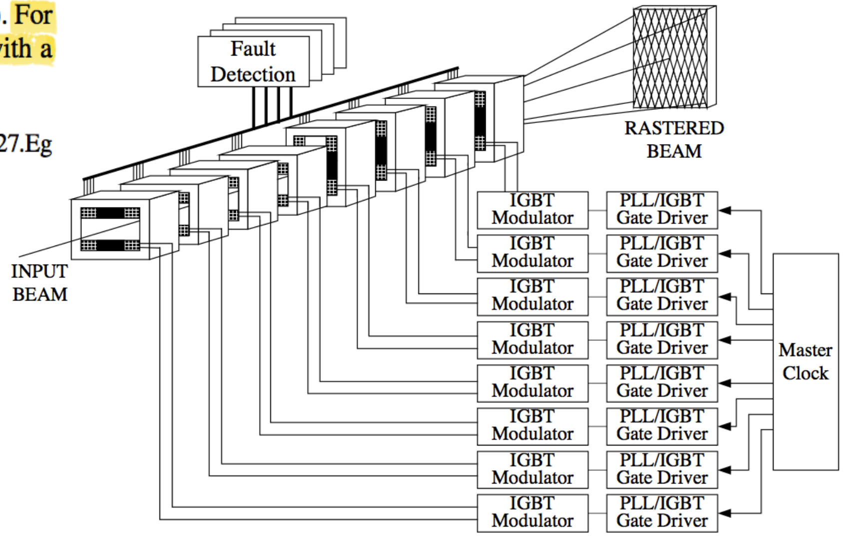
1322 Big Rock Loop, Los Alamos, New Mexico 87544, USA

(Received 5 November 2007; published 20 March 2008)

This Comment presents unpublished and published work done by Los Alamos National Laboratory (LANL) in the period 1990 to 1999 using the nonlinear focusing method outlined in the recent publication by Yuri *et al.* [Phys. Rev. ST Accel. Beams **10**, 104001 (2007)]. The LANL work included theory, design, modeling, and testing of nonlinear focusing beam "expanders" for use with high energy proton beams, including the proposed 1.7-GeV, 100-mA cw proton Accelerator for the Production of Tritium (APT). For several reasons listed in the text, the APT nonlinear focusing beam expander design was replaced with a high-frequency beam raster system.

DOI: 10.1103/PhysRevSTAB.11.039001 PACS numbers: 41.75.−i, 41.85.Ew, 29.27.Eg





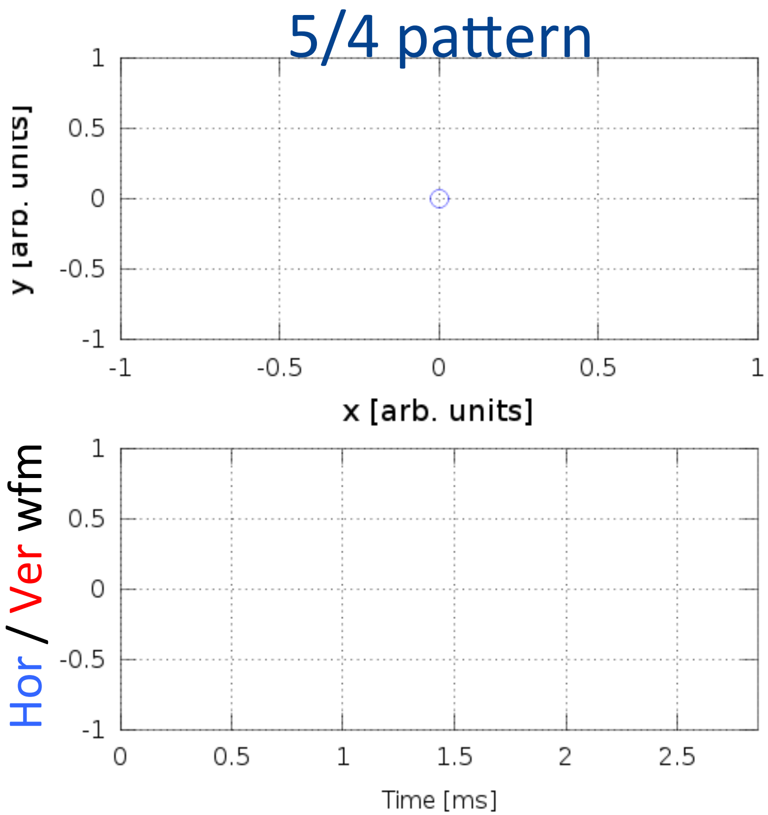
500 Hz – 600 Hz

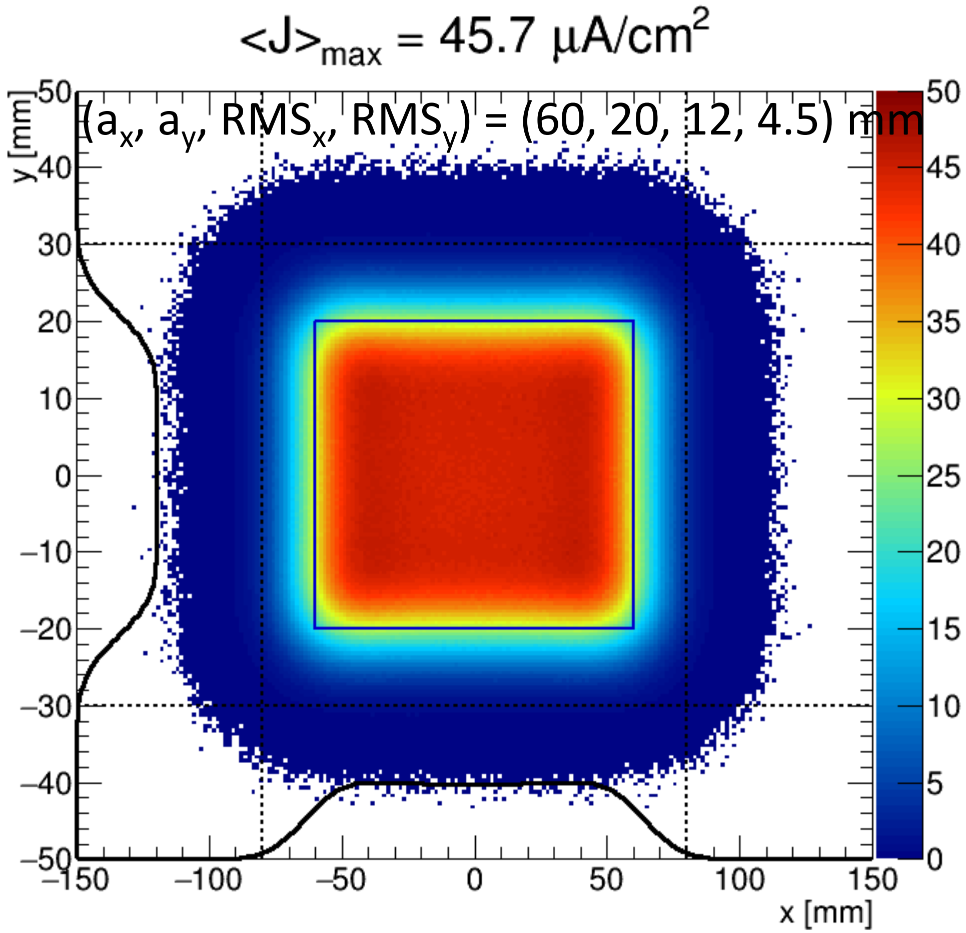
Lissajous Pattern

- Closed pattern (f_x/f_y, ϕ_{xy}, a_x, a_y) within a beam pulse,
- T_0 = 2.86 ms = (350 Hz)$^{-1}$ $f_x = n_x / T_0$, $f_y = n_y / T_0$
- Triangle waveforms => No lingering near edges, crosshatch
- $f_x / f_y \sim 1$ => A single (magnet + supply) design

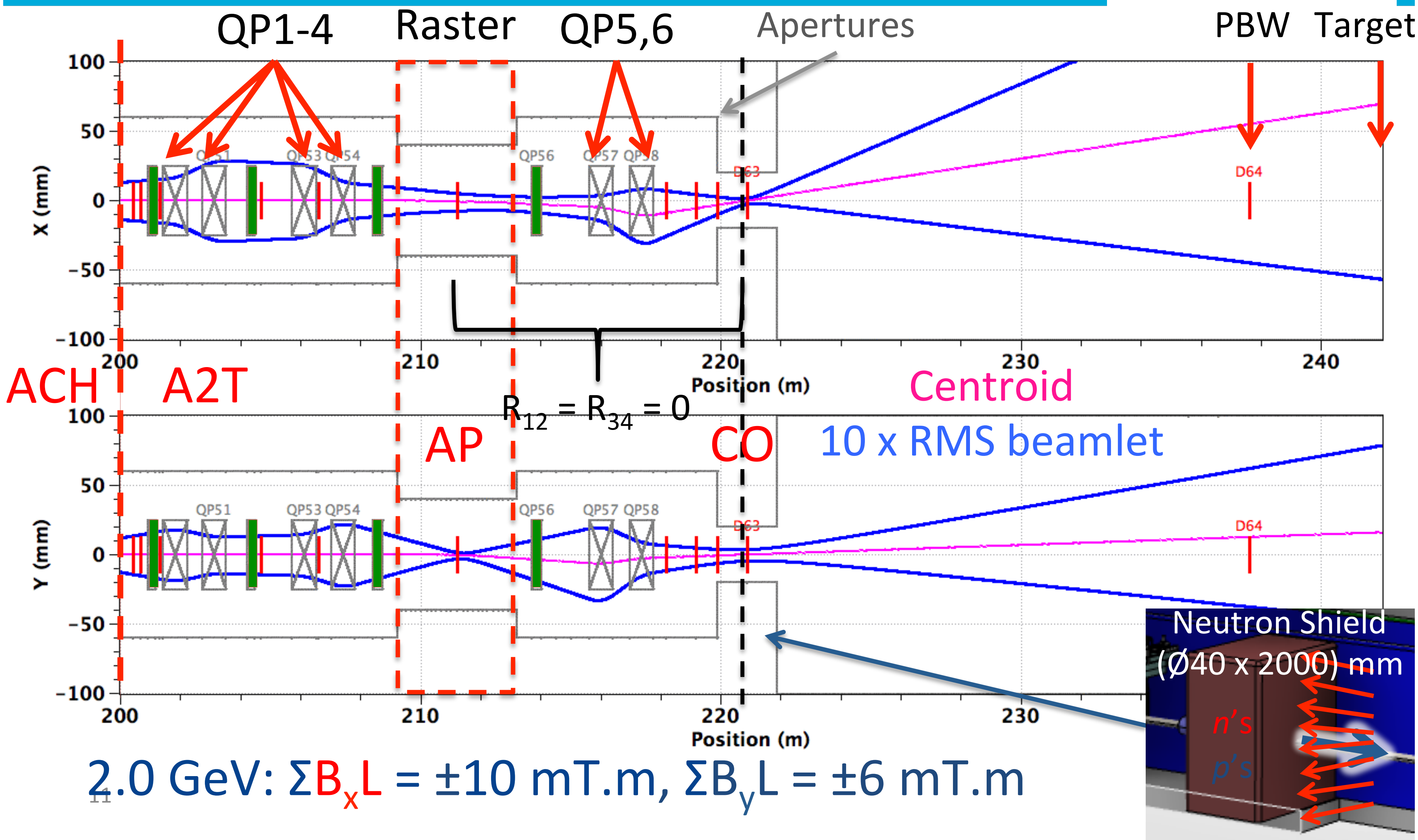
f_x = 39.6 kHz

f_y = 29.1 kHz





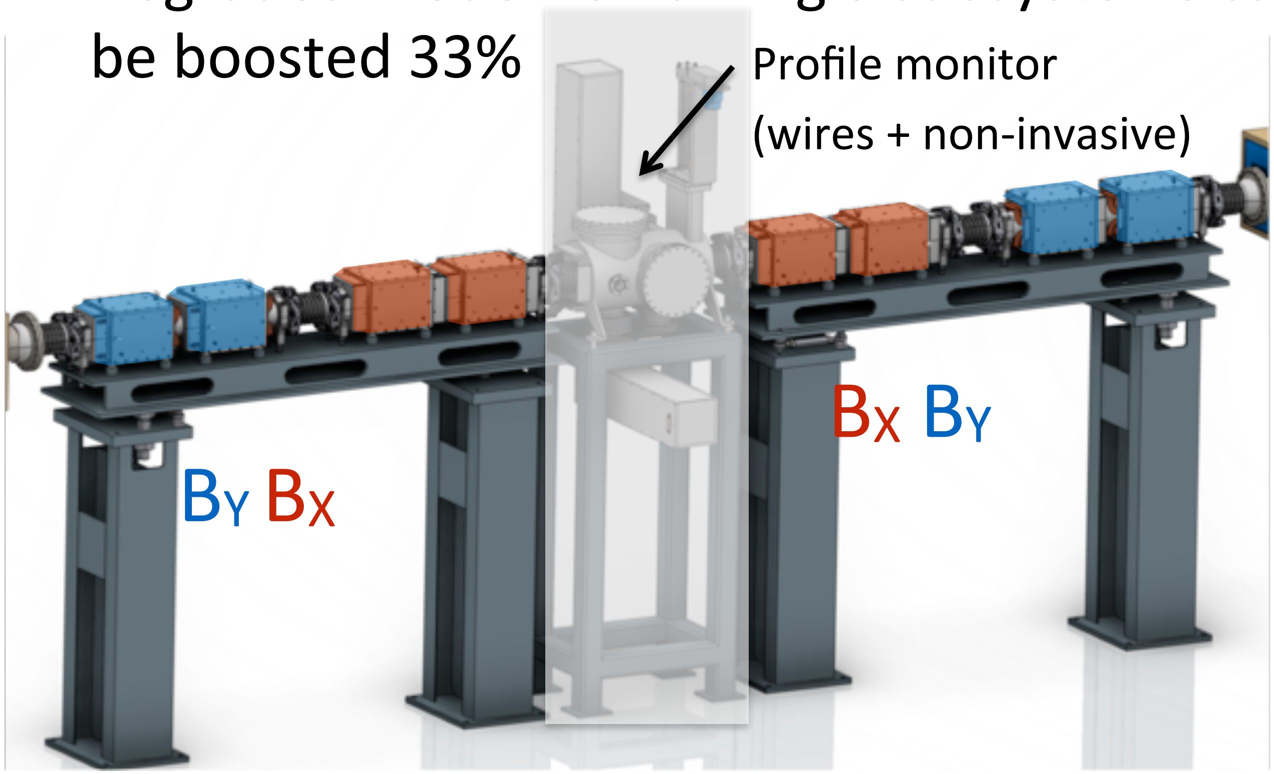
ESS A2T DC Beam Optics:
Similar to LANL MTS (B. Blind, LINAC'06, MOP055)

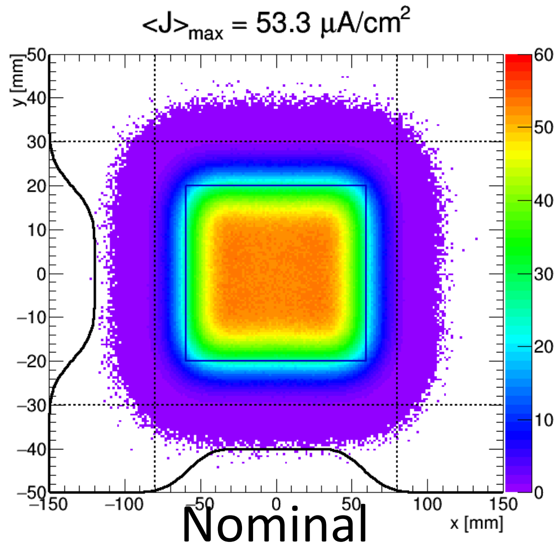


2.0 GeV: $\Sigma B_x L = \pm 10$ mT.m, $\Sigma B_y L = \pm 6$ mT.m

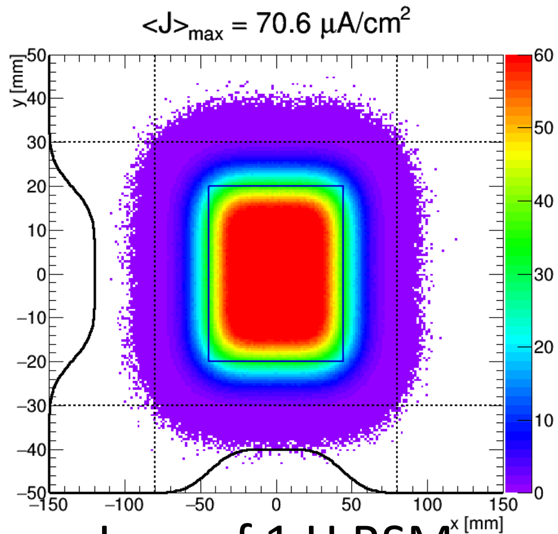
Modular Design: 4-Fold Redundancy

- 8 colinear magnets, 8 dedicated, identical supplies
- Localized failure => 75% amplitude retained
- Degraded mode: remaining 3 subsystems can be boosted 33%





Nominal

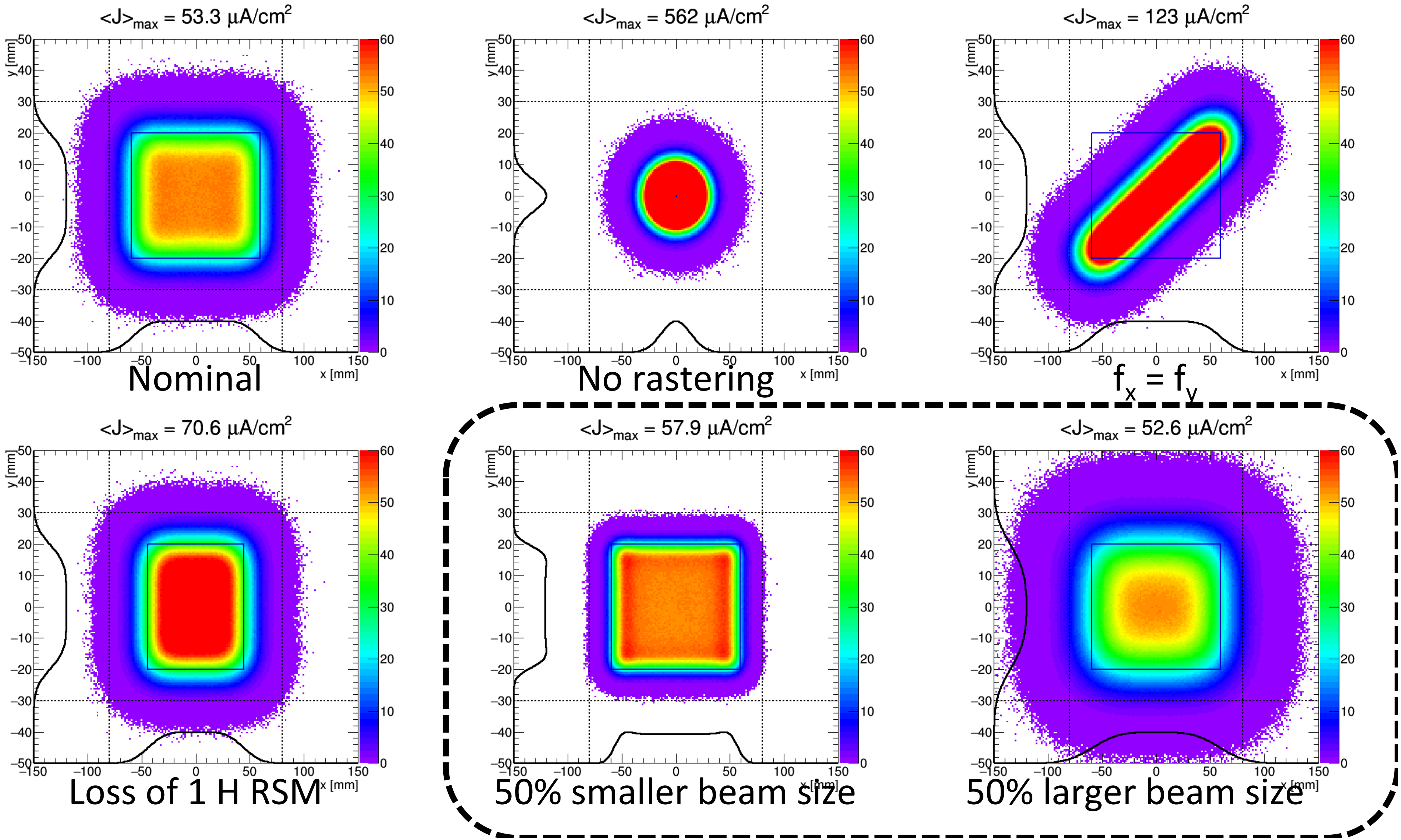


Loss of 1 H RSM

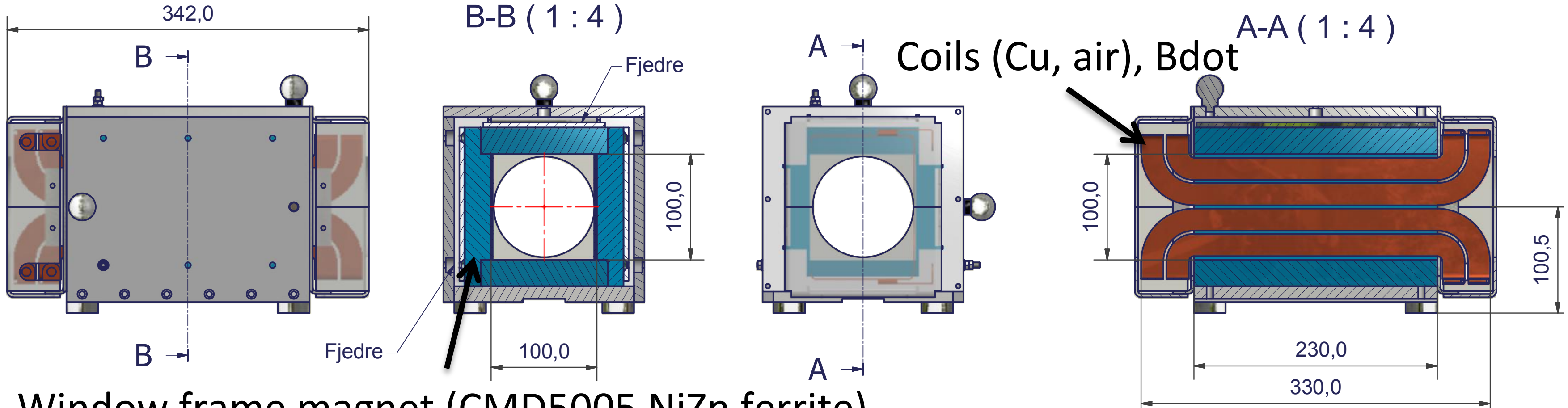
Raster Failure?

Figure of merit:

- Peak current density (J_{max}) on target
- Beam outside nominal footprint regions



Raster Scanning Magnet (RSM)



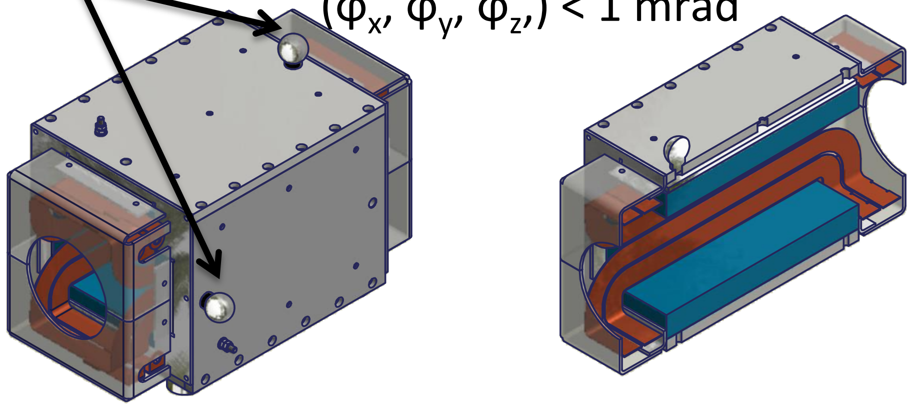
Coils (Cu, air), Bdot

Window frame magnet (CMD5005 NiZn ferrite)

Alignment targets

$(dx, dy) < 0.5$ mm, $dz < 0.3$ mm

$(\varphi_x, \varphi_y, \varphi_z,) < 1$ mrad

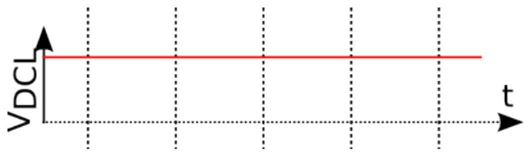


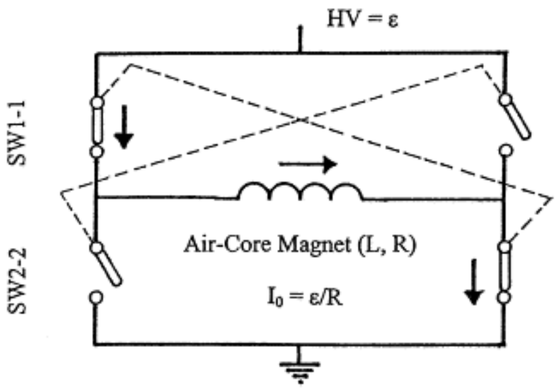
Field quality: $\Delta(\int Bdl)/\int Bdl < 10\%$ @ GFR = ± 15 mm

Table 1: Top level parameters and specifications of a RSM.

Parameter	Unit	Value
Beam rigidity	T.m	9.29
Beam pulse (4%)	ms	2.86
Raster pulse (5%)	ms	3.57
Max. f_w	kHz	40
Waveform	—	Triangle
Min. magnet aperture	mm	100
Magnetic length	mm	300
Turns per coil	—	2
Peak strength	mT.m	5
Nom. strength (H / V)	mT.m	1.6 / 2.3
Nom. deflection (H / V)	mrad	0.17 / 0.25
Max. current (peak-to-peak)	A	±340
Max. voltage (peak-to-peak)	V	±650

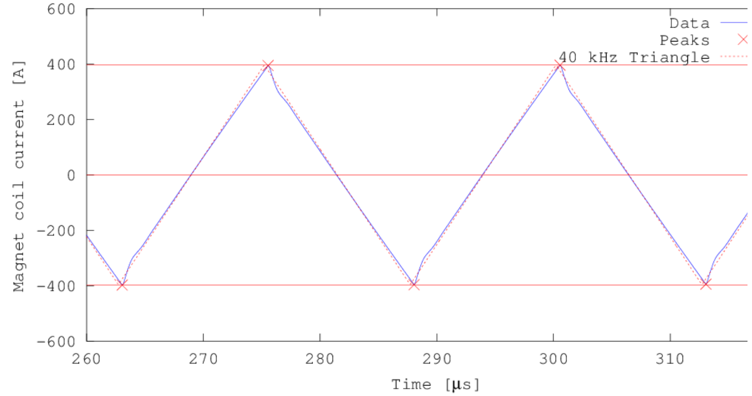
RSM Supply:
Capacitor charging DC + H bridge

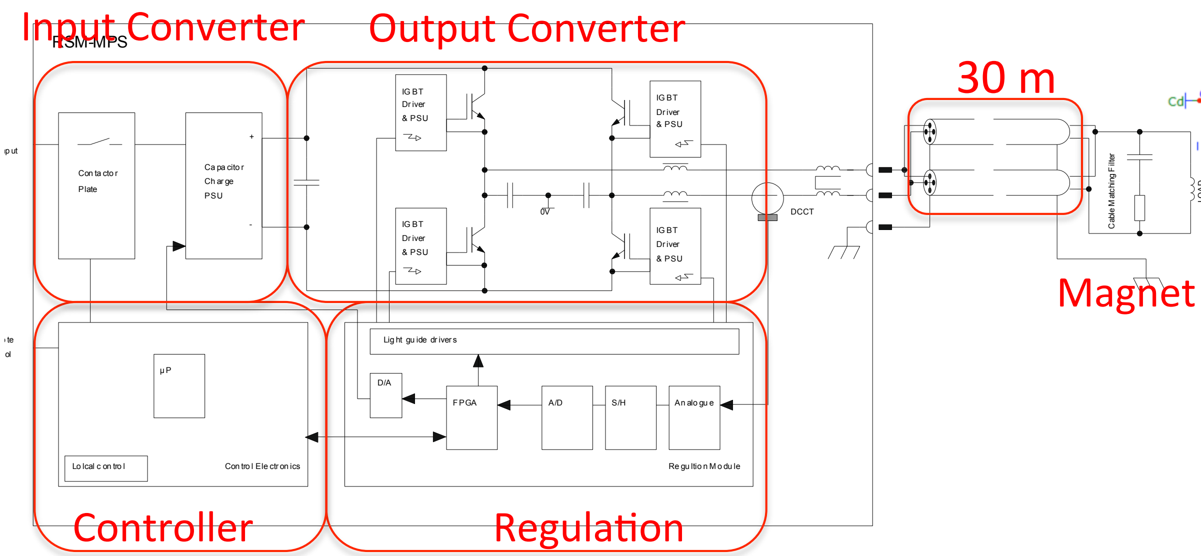


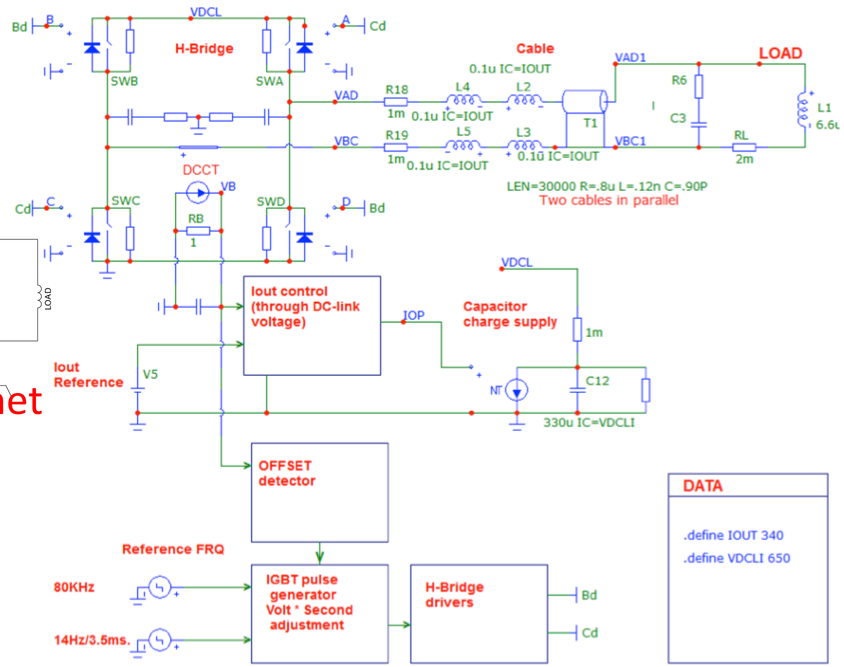


doi: 10.1016/j.nima.2004.09.034

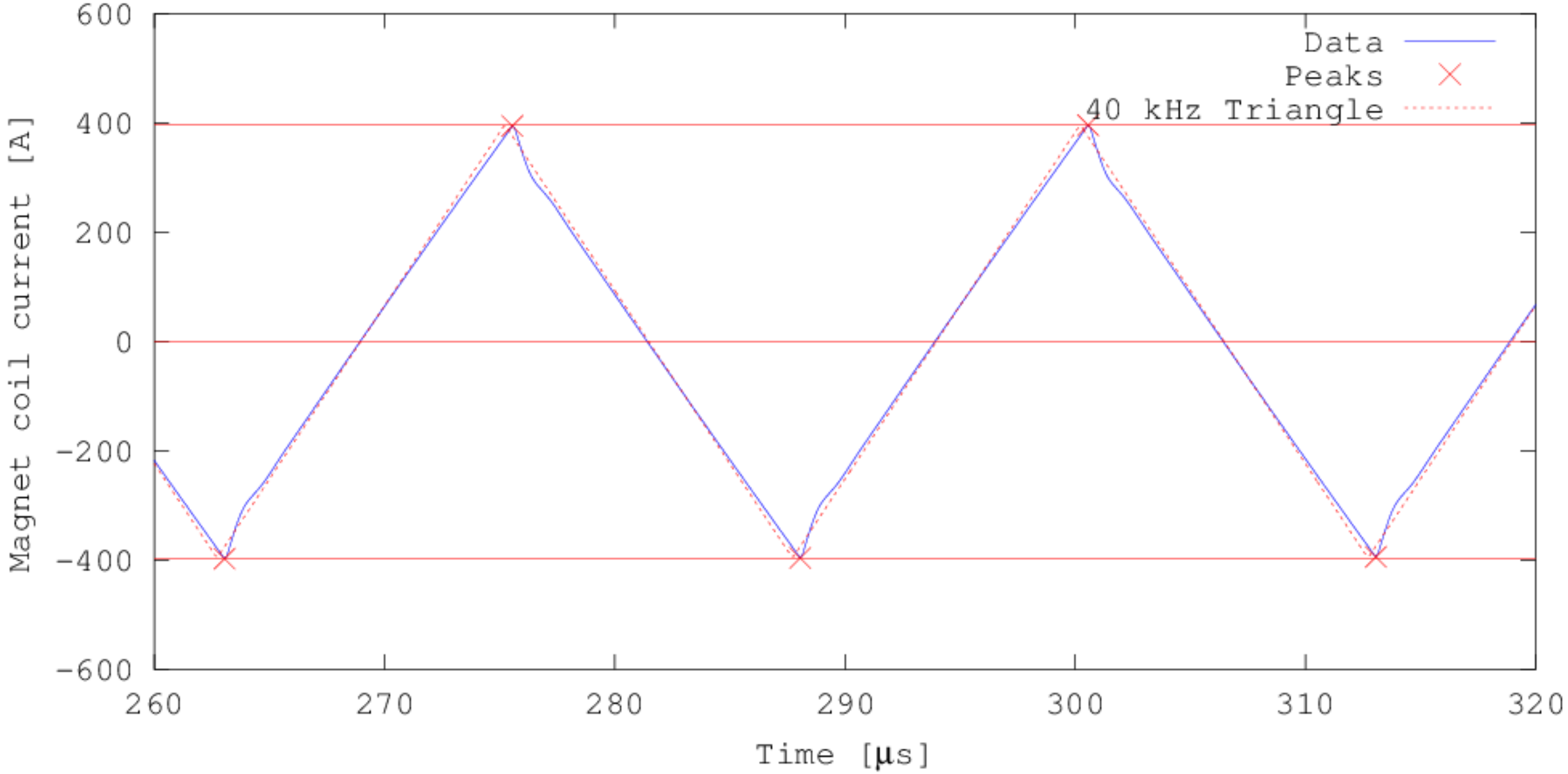
Simulated 40 kHz waveform







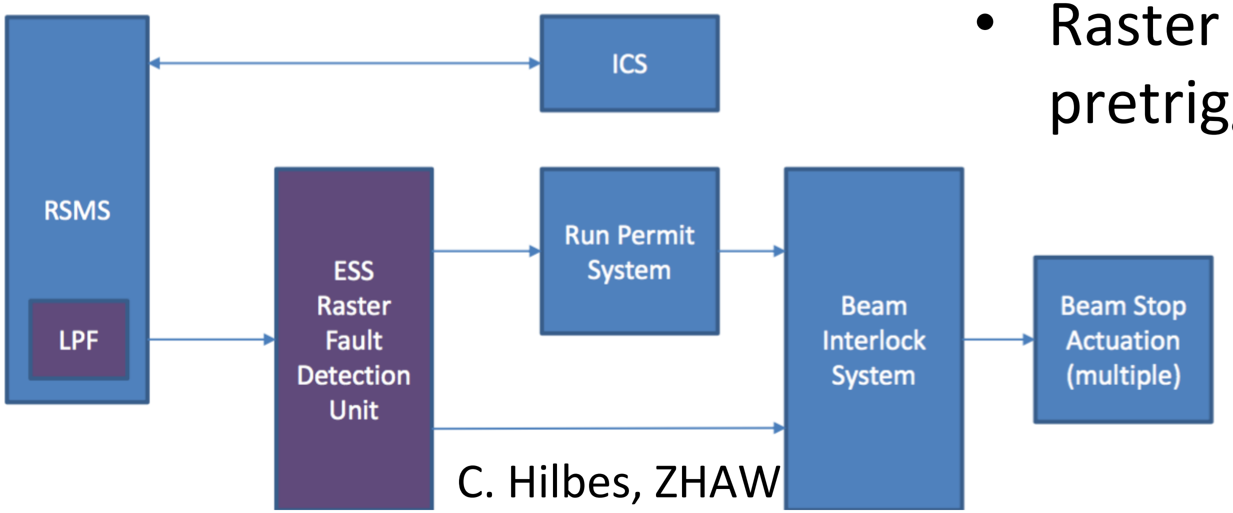
Simulated Waveform



RSM System Fault Detection?

Dedicated Fault Detection Unit (FDU)

- Bdot loops in each magnet (square wfms)
- (Idot current transformers?)
- Beam instrumentation
- RSM supply status



C. Hilbes, ZHAW

Local Protection Functions (supply)

- System self-verification preceding each(?) pulse
  - Capacitor charge supply
    - General supply status
    - DC link voltage
  - Temperatures, etc.
- Raster pulse relative to pretrigger

Summary & Outlook
Providing Uniform Beams? (ESS Experience)

- NLMs vs. RSMs?
  - Both concepts are proven and aesthetic
  - ESS: cost-neutral, ~1 M€
  - Acc./target/user requirements?

ESS Raster Experience

- Advantages:
  - Linear!
  - Intensity reduced considerably!
  - Decoupled tuning
- Drawback:
  - Supply complexity
  - Fault Detection Unit

- Fast raster system
  - Redundant (4 + 4), fail-safe raster system
  - 10 kHz–40 kHz, incl. 5th harm.
  - Robust (input beam)
  - Attractive to ADS
- Reduced level of contingency!
  - Acc. specs. (€!)
  - HEBT collimation removed
- Positive evaluation of hardware feasibility
  - 2-magnet complete pre-series (ultimo 2017):
  - Full production raster scanning system (ultimo 2018)

Acknowledgements

- LANL: Inherited several considerations and work done by experts
- ESS: **Tom Shea, Eric Pitcher**, Carlos Martins, David McGinnis, Alan Takibayev, Phillip Bentley, Paul Henry, Pascal Sabbagh, Annika Nordt, Iñigo Alonso, Han Lee,…
- CERN: Laurent Ducimetière *et al.,* Rüdiger Schmidt
- ZHAW: Christian Hilbes, Martin Rejz
- Danfysik: feasibility study + contract

Thank you for the attention!

Questions?