Raster Scanning Magnet System CDR-2

Validation of DDR & FAT-I

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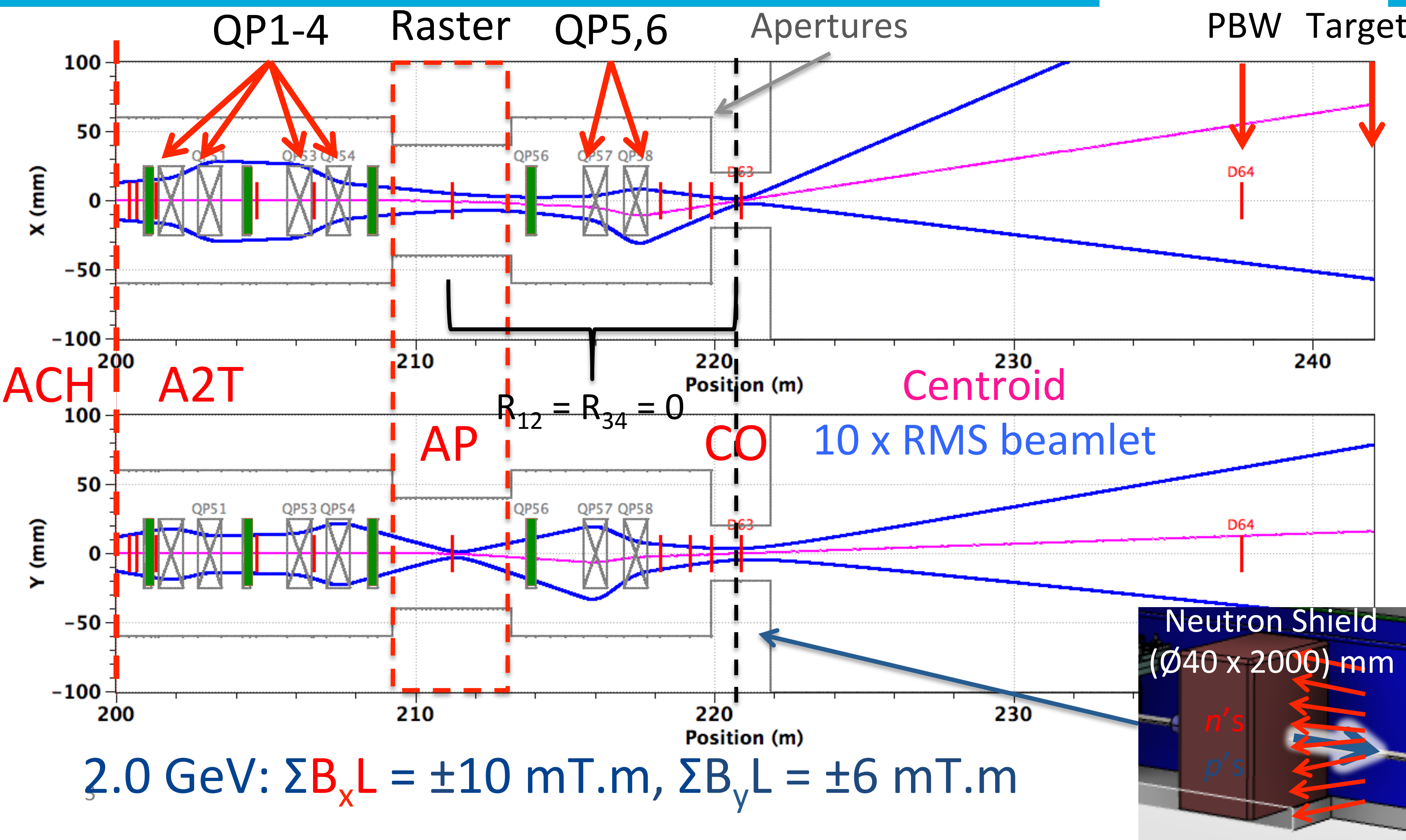
www.europeanspallationsource.se
January 13, 2017

System Requirements

- Shall raster the 0.2-2.0 GeV beam in both horizontal (H) and vertical (V) direction across the target
  - maintain distinct H&V amplitude setpoints
    - 5 mT.m / magnet (nominally B_yL =1.5 mT.m and B_xL =2.6 mT.m)
  - maintain distinct H&V frequency setpoints
    - configurable up to 40 kHz (10-40 kHz)
- Shall be synchronized to (and fully cover) the proton beam pulse (14 Hz x 3.57 ms = 5% duty cycle)
- Shall be robust towards localized component and configuration failures:
  - 4-fold redundancy in both planes, individually powered by dedicated (identical supplies)
- …

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

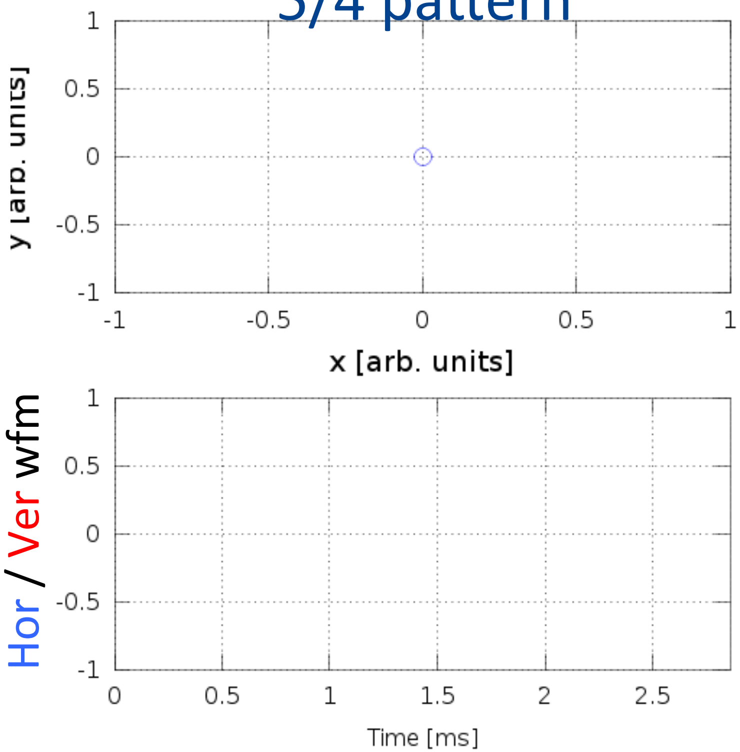
Lissajous Pattern

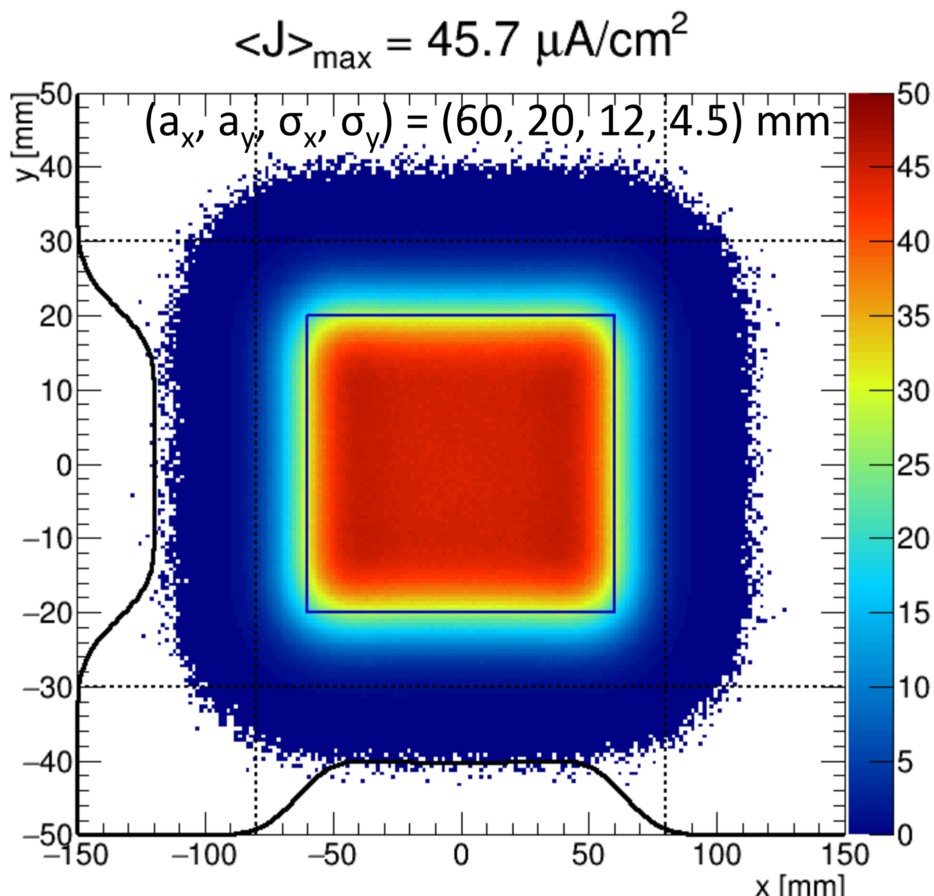
- Closed pattern (f_x/f_y, ϕ_{xy}, a_x, a_y) within a beam pulse:
- T_0 = 2.86 ms = $(350\ \text{Hz})^{-1}$ $f_x = n_x / T_0$, $f_y = n_y / T_0$
- Triangle waveforms => No lingering near edges, crosshatch
- $f_x / f_y \sim 1$ => A single (magnet + supply) design

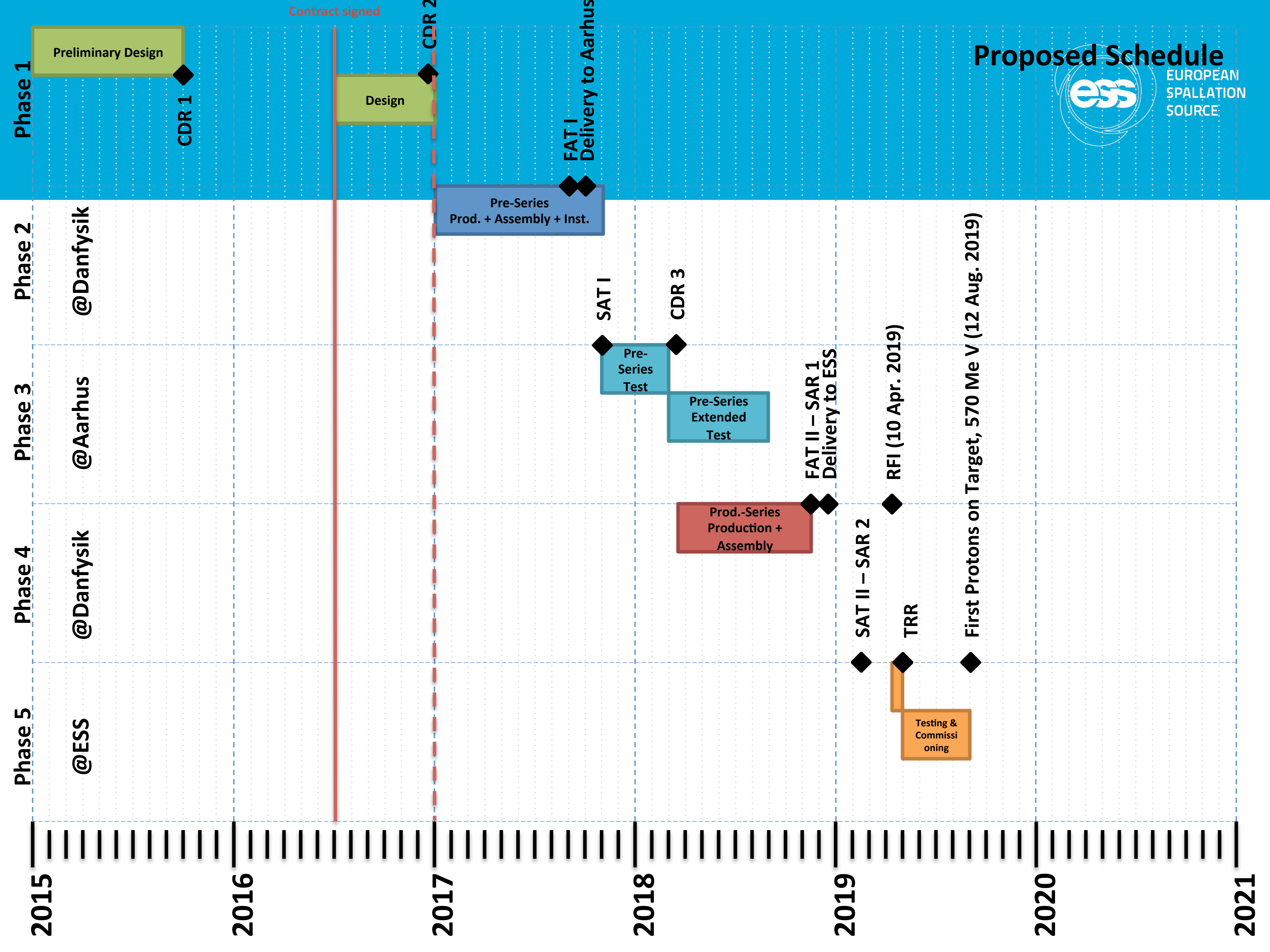
f_x = 39.6 kHz

f_y = 29.1 kHz

5/4 pattern







Proposed Schedule
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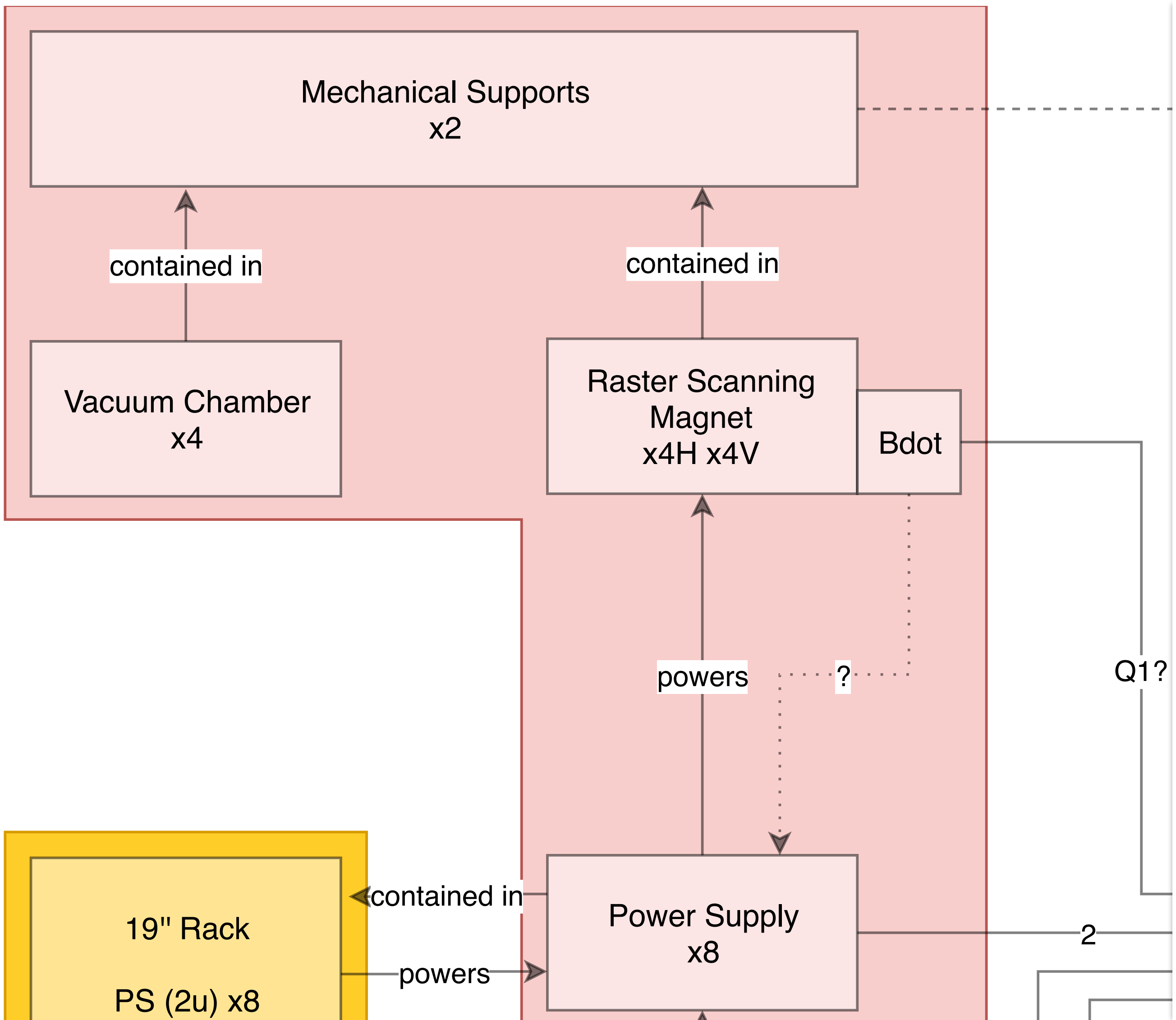
Contract signed
Phase 1
Phase 2
@Danfysik
Phase 3
@Aarhus
Phase 4
@Danfysik
Phase 5
@ESS
Preliminary Design
CDR 1
Design
CDR 2
FAT I
Delivery to Aarhus
Pre-Series Prod. + Assembly + Inst.
SAT I
CDR 3
Pre-Series Test
Pre-Series Extended Test
FAT II – SAR 1
Delivery to ESS
RFI (10 Apr. 2019)
First Protons on Target, 570 Me V (12 Aug. 2019)
Prod.-Series Production + Assembly
SAT II – SAR 2
TRR
Testing & Commissi oning
2015
2016
2017
2018
2019
2020
2021

RSM Past, Present & Future

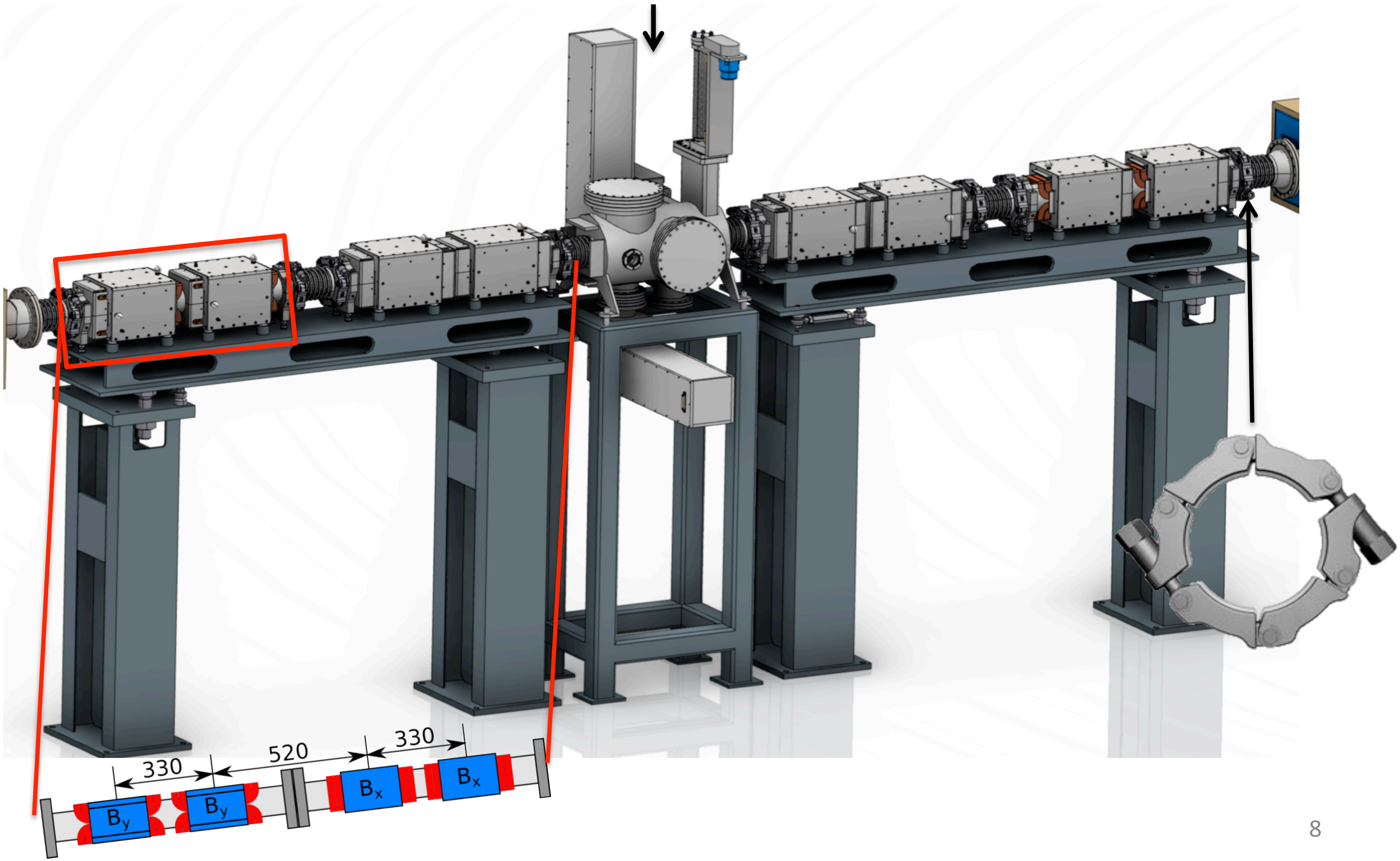
- 2015.10.08, CDR-1: to start procurement
- 2016.06.01, Contract signed with Danfysik
- Long-Lead Items (ceramic chambers, ferrites, MOSFETs, …):
  - Schedule is based on a swift approval of design and/or a collaborative effort in improving the design to make it match ESS' *preferences*.
  - Delays / late changes could significantly delay schedule and excessively increase the total cost!
- Early 2018, CDR-3: approving the performance of the pre-series

A Crude Block Diagram



Hardware: Magnets + Support

Profile monitor (wires + non-invasive)



RSM Supply (feasibility study level)

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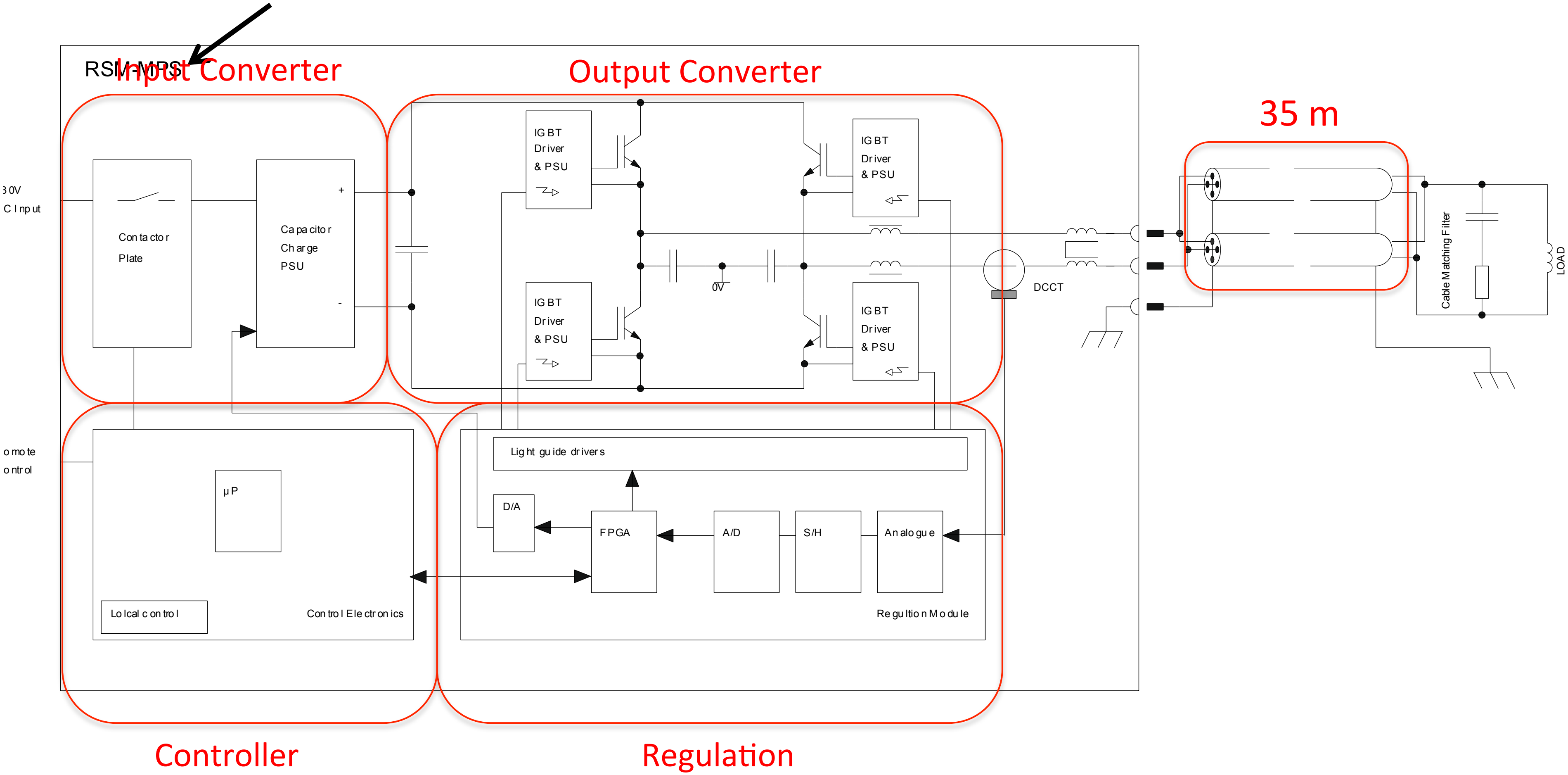
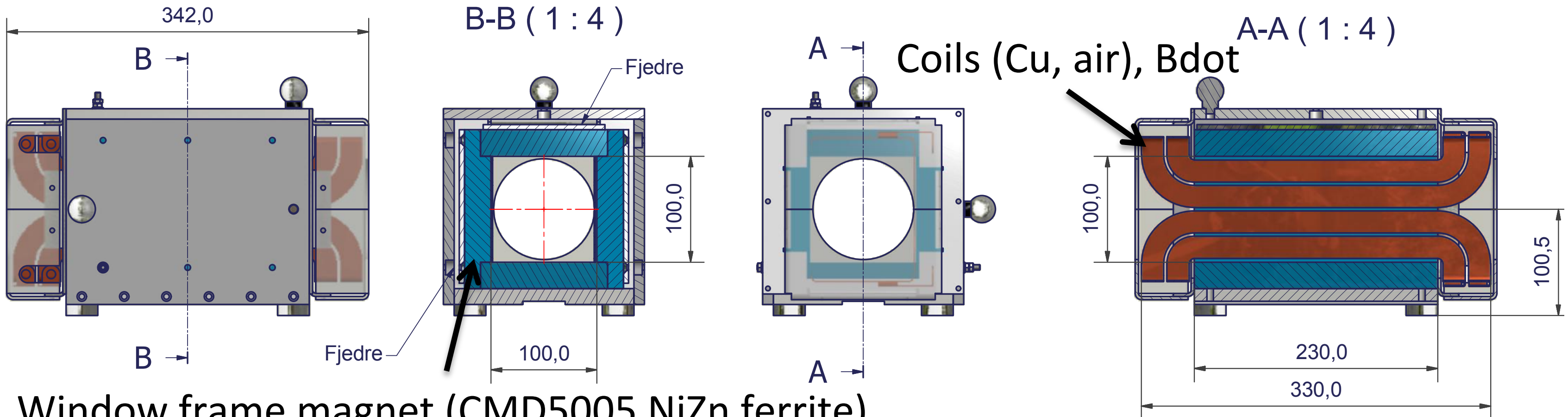
(MPS: Magnet Power Supply)



Magnets

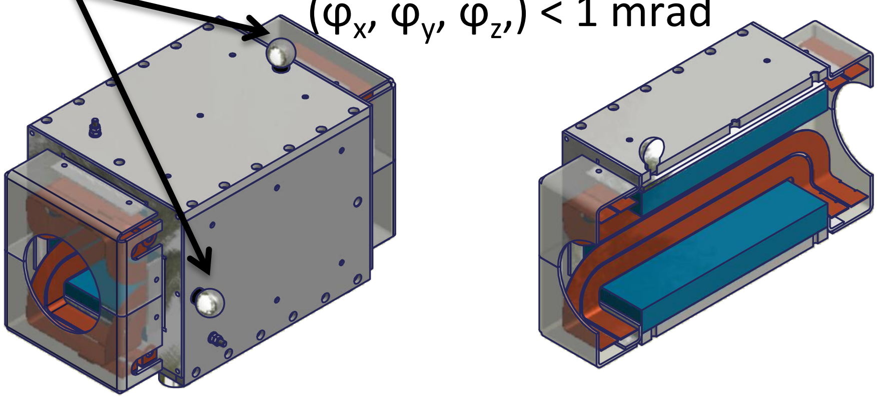
Raster Scanning Magnet (RSM)



Window frame magnet (CMD5005 NiZn ferrite)

Alignment targets (dx, dy) < 0.5 mm, dz < 0.3 mm

(φ_x, φ_y, φ_z) < 1 mrad



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

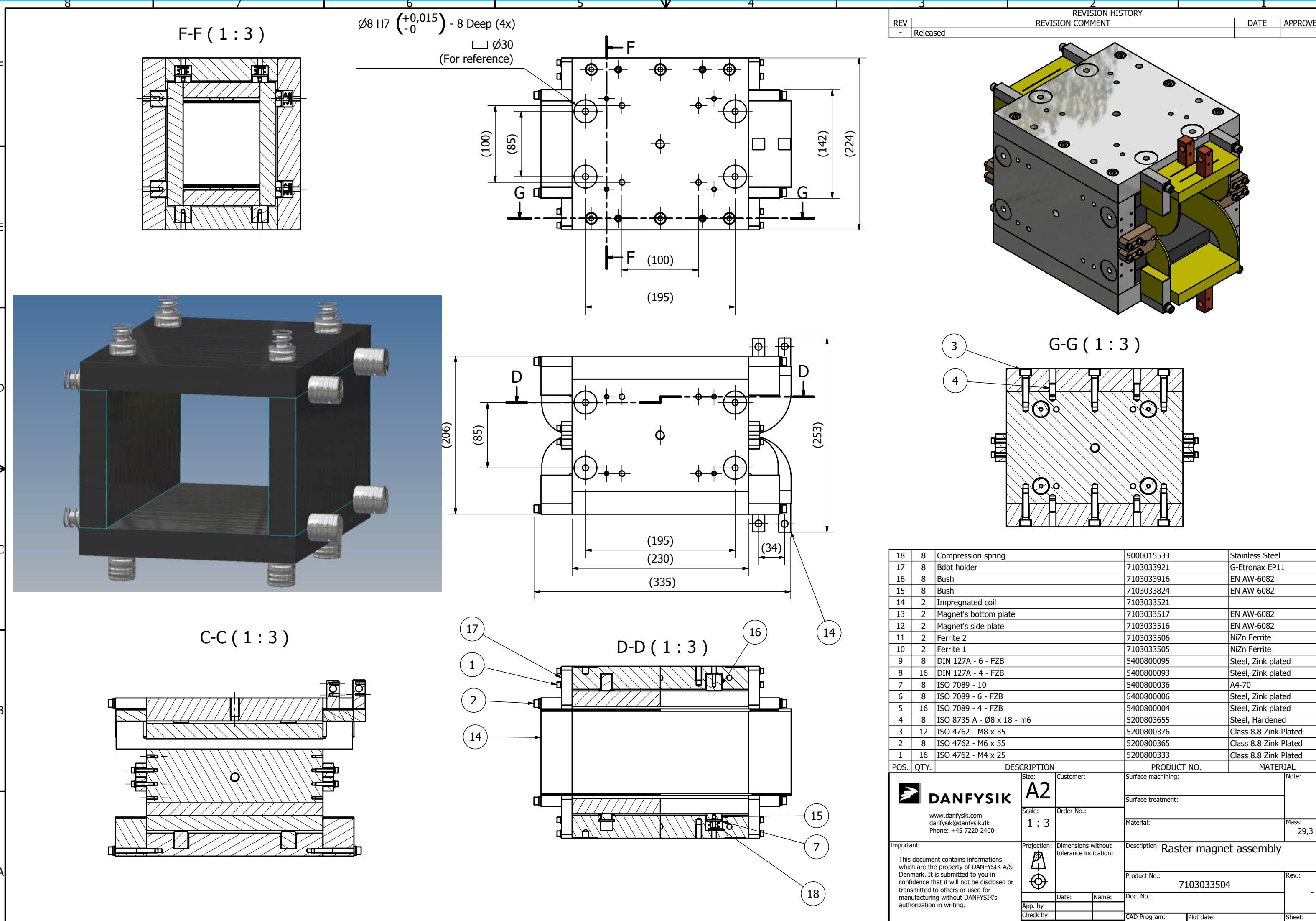
Table 1: Top level parameters and specifications of a RSM.

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

Magnetic Field Studies – 2D & 3D

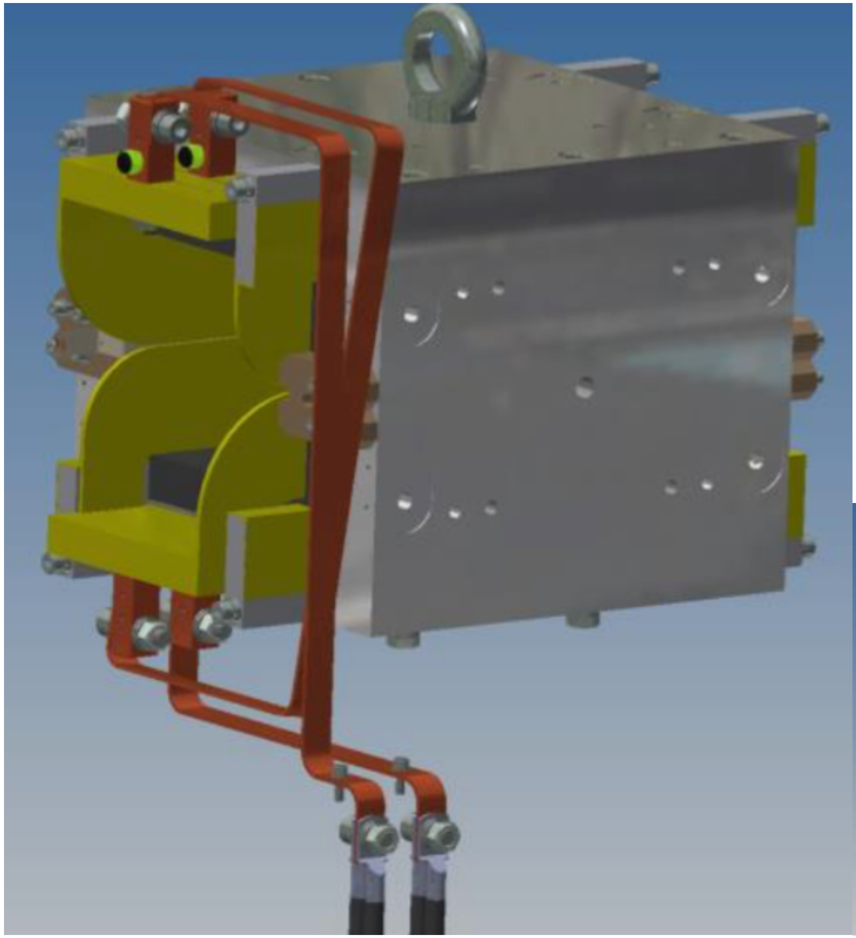
- Using the transient module in Opera 2D, eddy current and proximity effects have been evaluated
  - current distributions are affected but the design is not compromised at 40 kHz (skin depth ~0.3 mm in Cu)
- Only minor surprises found:
  - The inductance is found to be larger than the analytical calculation.
- Integrated field homogeneity is found to be 1% @ GFR (spec. was <10%)
- Thermal calculation: ~15 W (300 W @ 5% duty cycle) is dissipated in each magnet

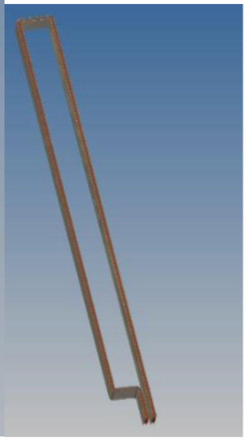
Raster Scanning Magnet (RSM)

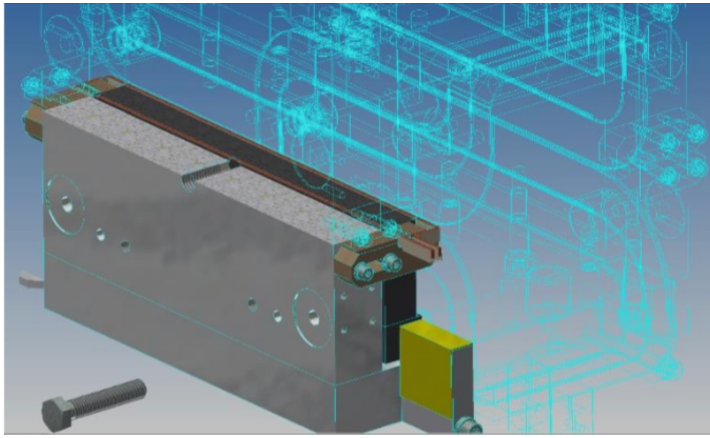


POS.	QTY.	DESCRIPTION	PRODUCT NO.	MATERIAL
18	8	Compression spring	9000015533	Stainless Steel
17	8	Bdot holder	7103033921	G-Etronax EP11
16	8	Bush	7103033916	EN AW-6082
15	8	Bush	7103033824	EN AW-6082
14	2	Impregnated coil	7103033521	
13	2	Magnet's bottom plate	7103033517	EN AW-6082
12	2	Magnet's side plate	7103033516	EN AW-6082
11	2	Ferrite 2	7103033506	NiZn Ferrite
10	2	Ferrite 1	7103033505	NiZn Ferrite
9	8	DIN 127A - 6 - FZB	5400800095	Steel, Zink plated
8	16	DIN 127A - 4 - FZB	5400800093	Steel, Zink plated
7	8	ISO 7089 - 10	5400800036	A4-70
6	8	ISO 7089 - 6 - FZB	5400800006	Steel, Zink plated
5	16	ISO 7089 - 4 - FZB	5400800004	Steel, Zink plated
4	8	ISO 8735 A - Ø8 x 18 - m6	5200803655	Steel, Hardened
3	12	ISO 4762 - M8 x 35	5200800376	Class 8.8 Zink Plated
2	8	ISO 4762 - M6 x 55	5200800365	Class 8.8 Zink Plated
1	16	ISO 4762 - M4 x 25	5200800333	Class 8.8 Zink Plated

RSM Connections







- Bus bars at top and bottom of coil ends
- Bdot loop: 1 / RSM
  - a single loop around return yoke
  - ± 51 V at full amplitude

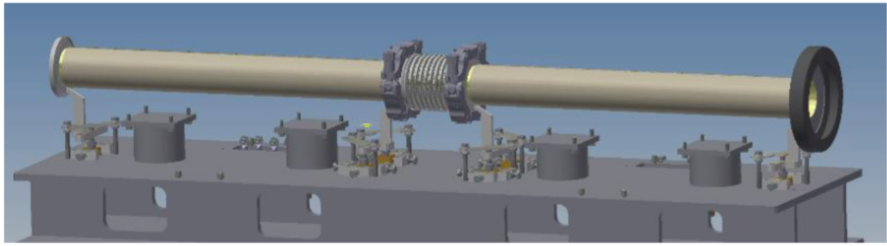
Vacuum Chambers & Support Structures

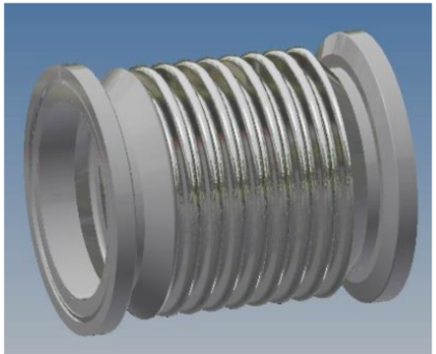
Vacuum System

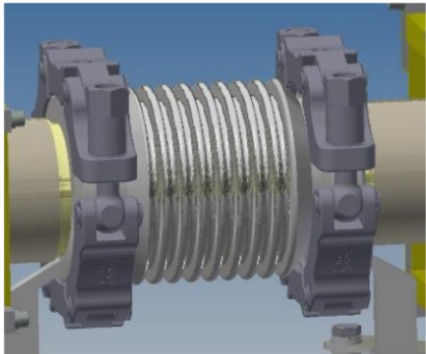
Vacuum system consists of

- Ceramic (Al2O2) chambers at the RSMs
- Quick Conflat flanges
- Hydro-formed bellows, ID Ø120 mm
- No pumps, gauges, etc. are relevant
- No metallization layer is provided (but prepared)

- Two families of chambers, differing only by the flange sizes
  – QCF100+QCF100 or QCF100+QCF160
  – Consider spares…







Ceramic Chambers

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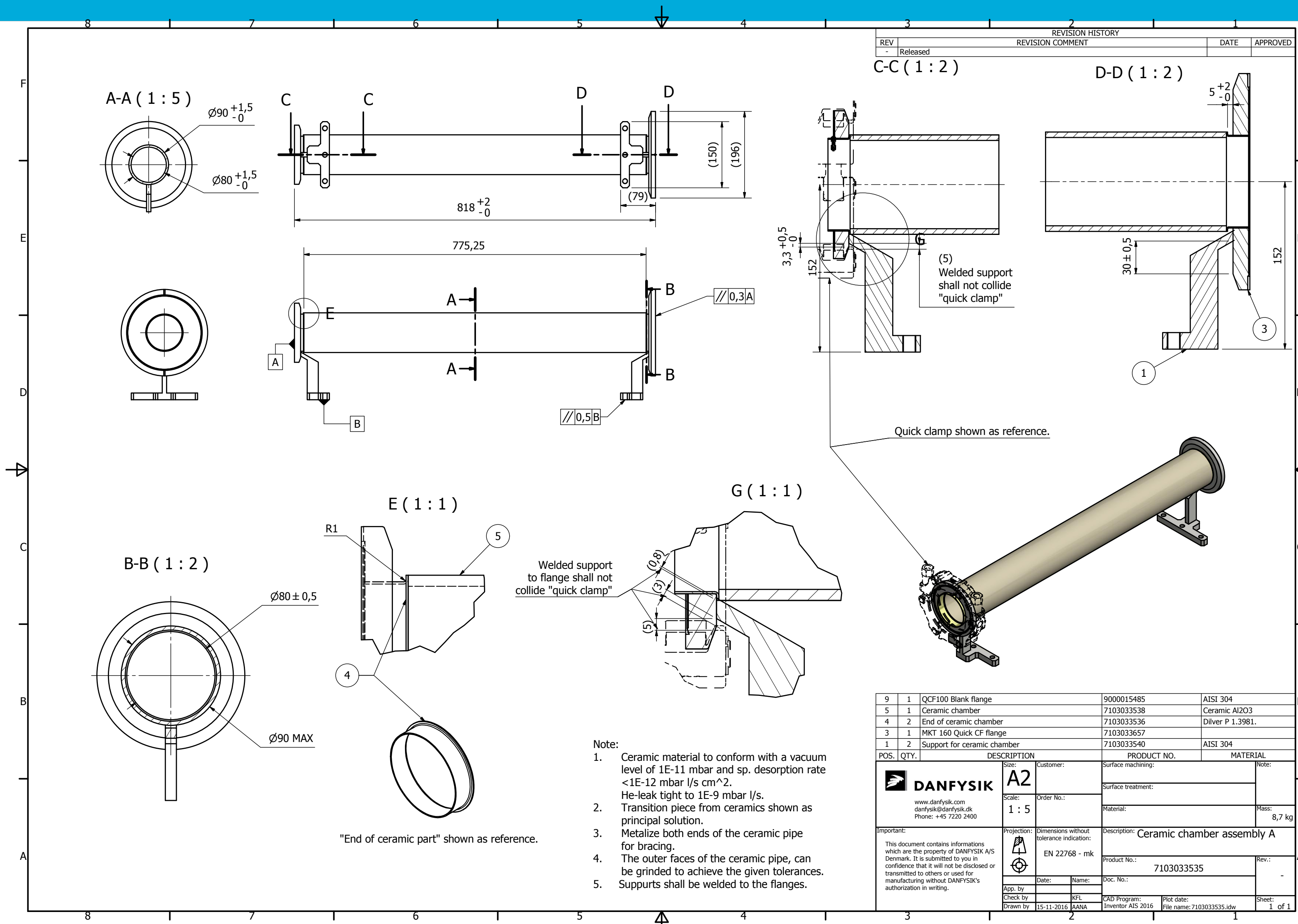
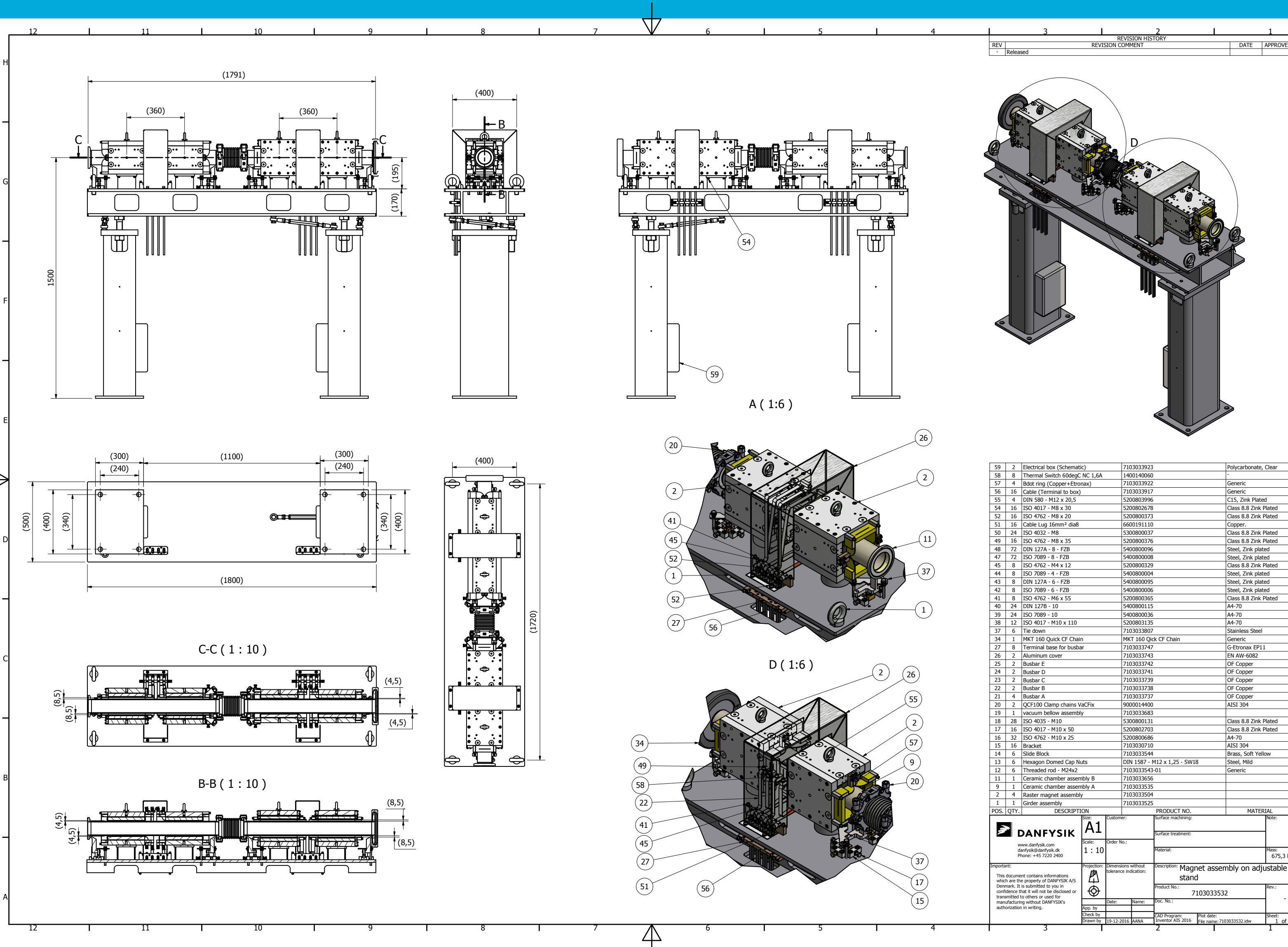


RSM Support (1 of 2)

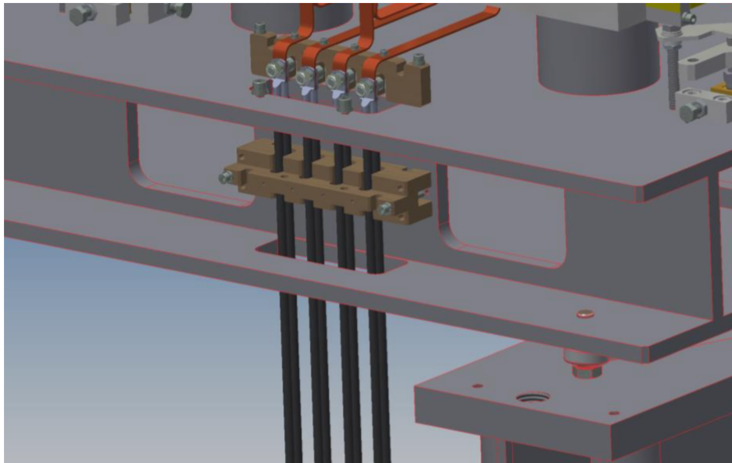
EUROPEAN SPALLATION SOURCE



POS.	QTY.	DESCRIPTION	PRODUCT NO.	MATERIAL
59	2	Electrical box (Schematic)	7103033923	Polycarbonate, Clear
58	8	Thermal Switch 60degC NC 1,6A	1400140060	-
57	4	Bdot ring (Copper+Etronax)	7103033922	Generic
56	16	Cable (Terminal to box)	7103033917	Generic
55	4	DIN 580 - M12 x 20,5	5200803996	C15, Zink Plated
54	16	ISO 4017 - M8 x 30	5200802678	Class 8.8 Zink Plated
52	16	ISO 4762 - M8 x 20	5200800373	Class 8.8 Zink Plated
51	16	Cable Lug 16mm² dia8	6600191110	Copper.
50	24	ISO 4032 - M8	5300800037	Class 8.8 Zink Plated
49	16	ISO 4762 - M8 x 35	5200800376	Class 8.8 Zink Plated
48	72	DIN 127A - 8 - FZB	5400800096	Steel, Zink plated
47	72	ISO 7089 - 8 - FZB	5400800008	Steel, Zink plated
45	8	ISO 4762 - M4 x 12	5200800329	Class 8.8 Zink Plated
44	8	ISO 7089 - 4 - FZB	5400800004	Steel, Zink plated
43	8	DIN 127A - 6 - FZB	5400800095	Steel, Zink plated
42	8	ISO 7089 - 6 - FZB	5400800006	Steel, Zink plated
41	8	ISO 4762 - M6 x 55	5200800365	Class 8.8 Zink Plated
40	24	DIN 127B - 10	5400800115	A4-70
39	24	ISO 7089 - 10	5400800036	A4-70
38	12	ISO 4017 - M10 x 110	5200803135	A4-70
37	6	Tie down	7103033807	Stainless Steel
34	1	MKT 160 Quick CF Chain	MKT 160 Qick CF Chain	Generic
27	8	Terminal base for busbar	7103033747	G-Etronax EP11
26	2	Aluminum cover	7103033743	EN AW-6082
25	2	Busbar E	7103033742	OF Copper
24	2	Busbar D	7103033741	OF Copper
23	2	Busbar C	7103033739	OF Copper
22	2	Busbar B	7103033738	OF Copper
21	4	Busbar A	7103033737	OF Copper
20	2	QCF100 Clamp chains VaCFix	9000014400	AISI 304
19	1	vacuum bellow assembly	7103033683	
18	28	ISO 4035 - M10	5300800131	Class 8.8 Zink Plated
17	16	ISO 4017 - M10 x 50	5200802703	Class 8.8 Zink Plated
16	32	ISO 4762 - M10 x 25	5200800686	A4-70
15	16	Bracket	7103030710	AISI 304
14	6	Slide Block	7103033544	Brass, Soft Yellow
13	6	Hexagon Domed Cap Nuts	DIN 1587 - M12 x 1,25 - SW18	Steel, Mild
12	6	Threaded rod - M24x2	7103033543-01	Generic
11	1	Ceramic chamber assembly B	7103033656	
9	1	Ceramic chamber assembly A	7103033535	
2	4	Raster magnet assembly	7103033504	
1	1	Girder assembly	7103033525	

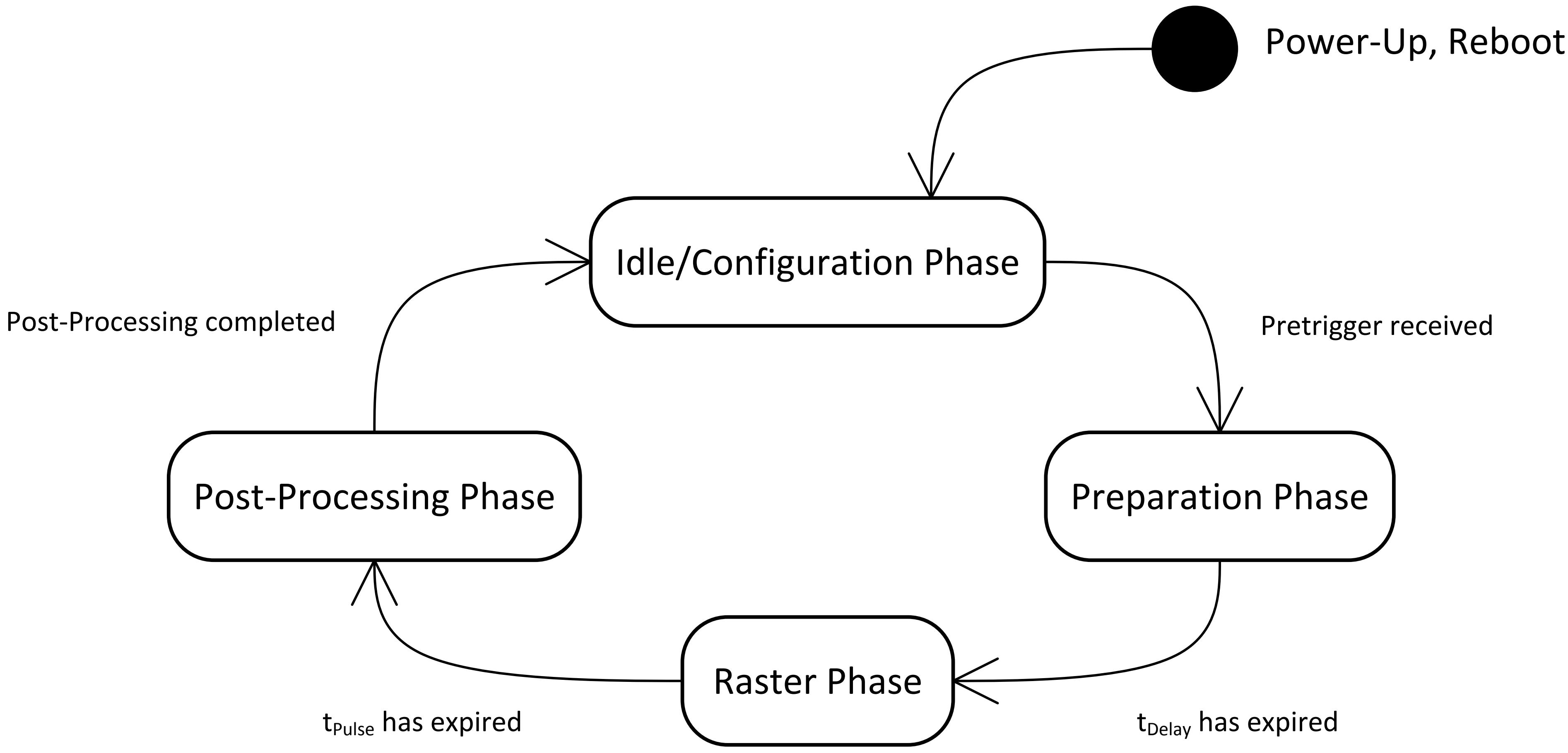
Support

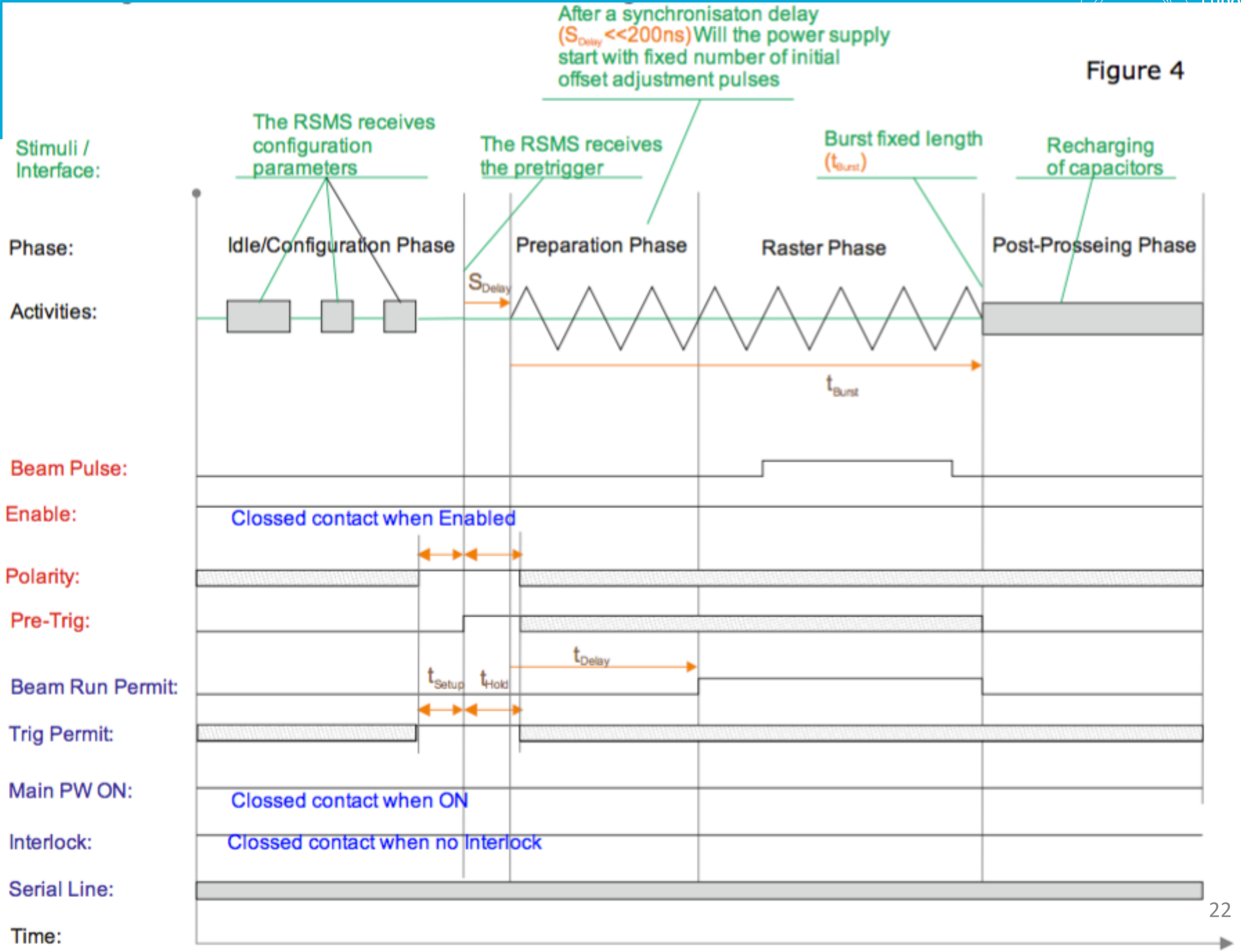
- Girder-based: most elements are fixed to precision-machined surfaces on a girder that is aligned as a rigid body relative to two feet.
  - magnet-to-magnet alignment will be checked within a girder section during assembly
- 3 screws + 3 turnbuckles provide six degree of freedom for alignment of the girder
- A total of ±25 mm horizontal range and ±35 vertical range
- Alignment – iterate:
  - reach nominal beam height of 1500 mm
  - angular alignment to ±0.1° (pitch/yaw/roll)
  - transverse adjustments
- RSM housing top plate features
  - a set of alignment fiducial holes
  - room for a precision level gauge



RSM Power Supply (RSMPS)

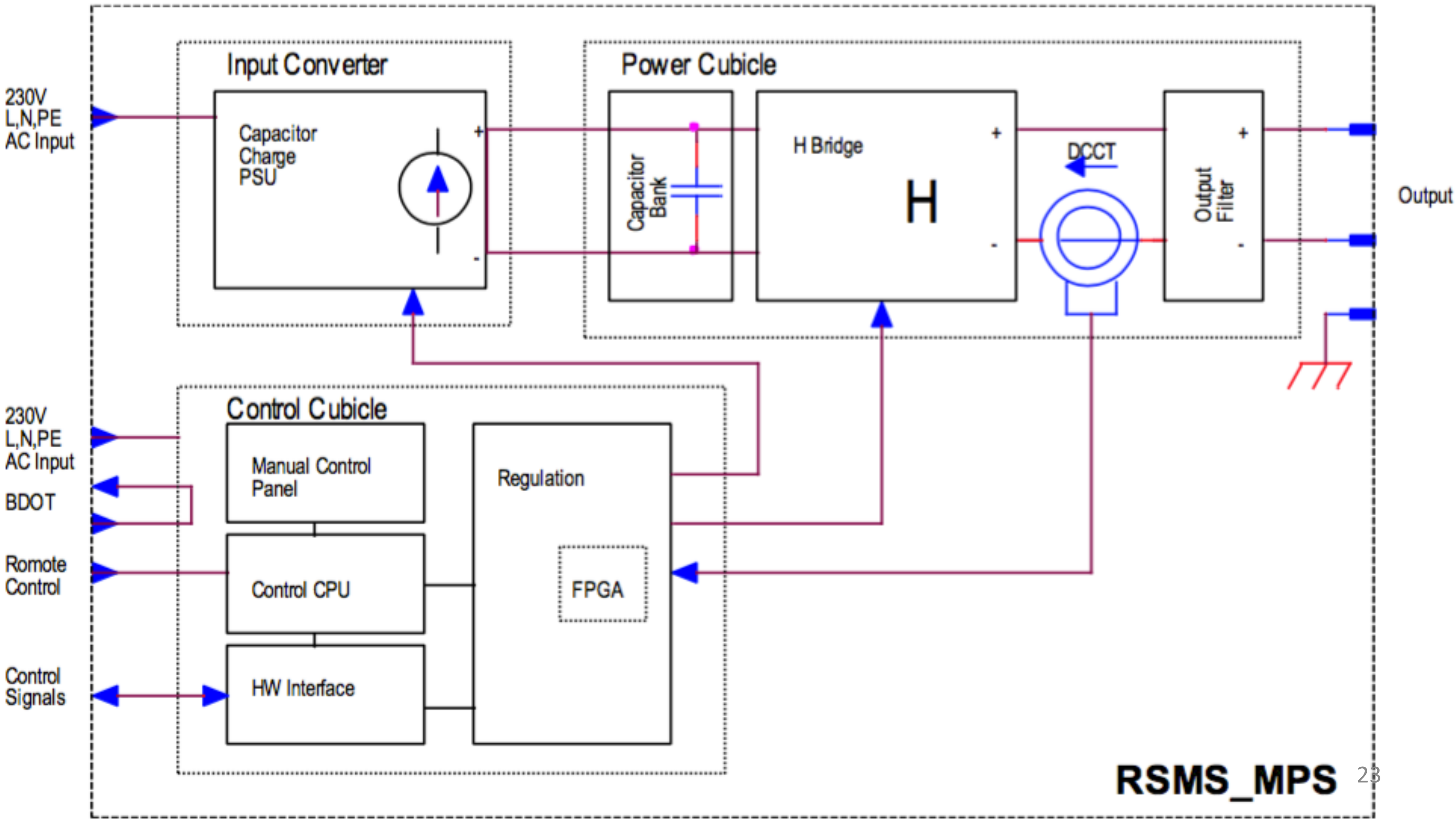
RSM Supply Algorithm

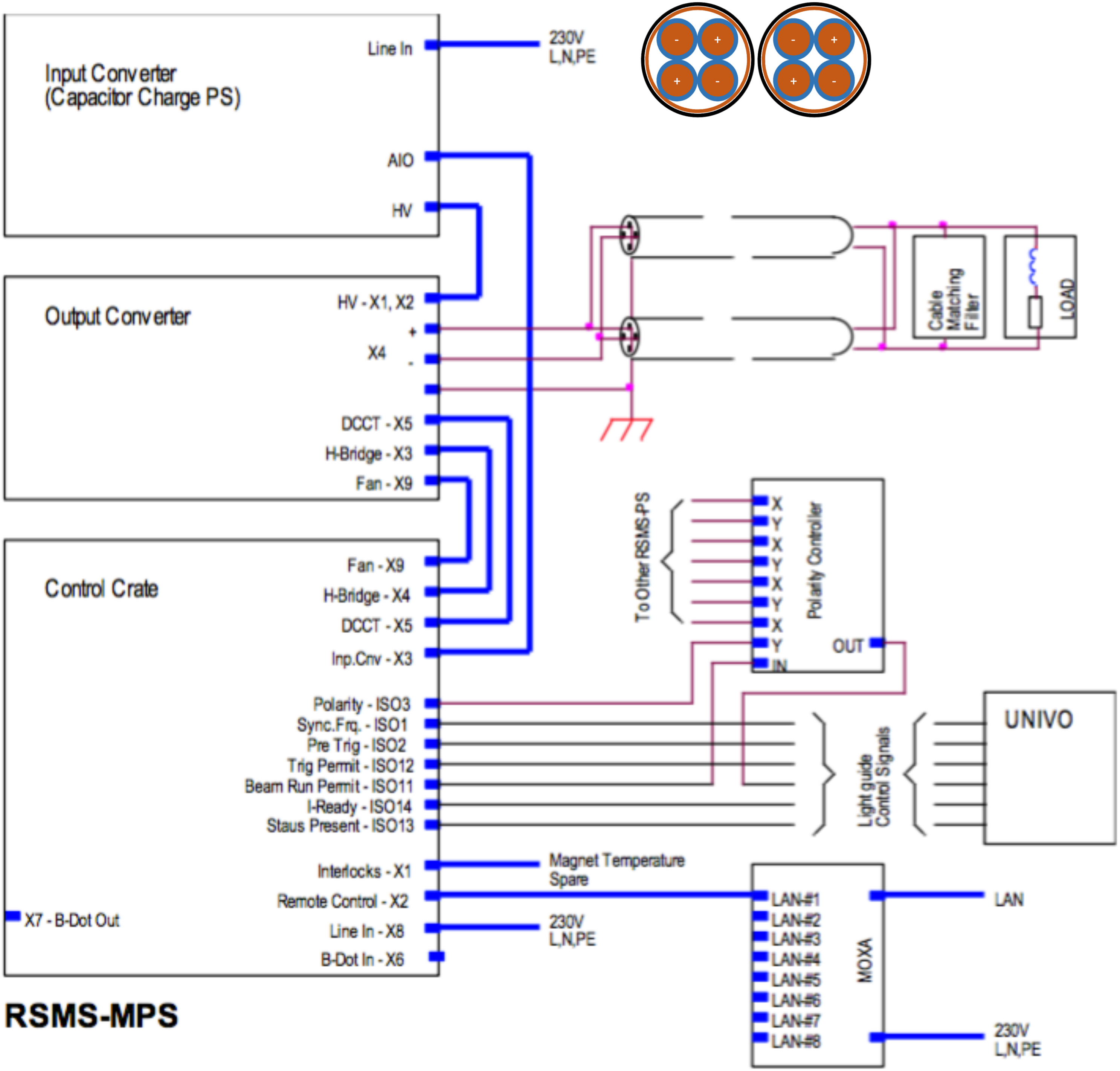




After a synchronisaton delay
(S_{Delay}<<200ns) Will the power supply
start with fixed number of initial
offset adjustment pulses
Figure 4
Stimuli /
Interface:
The RSMS receives
configuration
parameters
The RSMS receives
the pretrigger
Burst fixed length
(t_{Burst})
Recharging
of capacitors
Phase:
Idle/Configuration Phase
Preparation Phase
Raster Phase
Post-Prosseing Phase
Activities:
S_{Delay}
t_{Burst}
Beam Pulse:
Enable:
Clossed contact when Enabled
Polarity:
Pre-Trig:
t_{Delay}
Beam Run Permit:
t_{Setup}
t_{Hold}
Trig Permit:
Main PW ON:
Clossed contact when ON
Interlock:
Clossed contact when no Interlock
Serial Line:
Time:

RSMPS Block Diagram

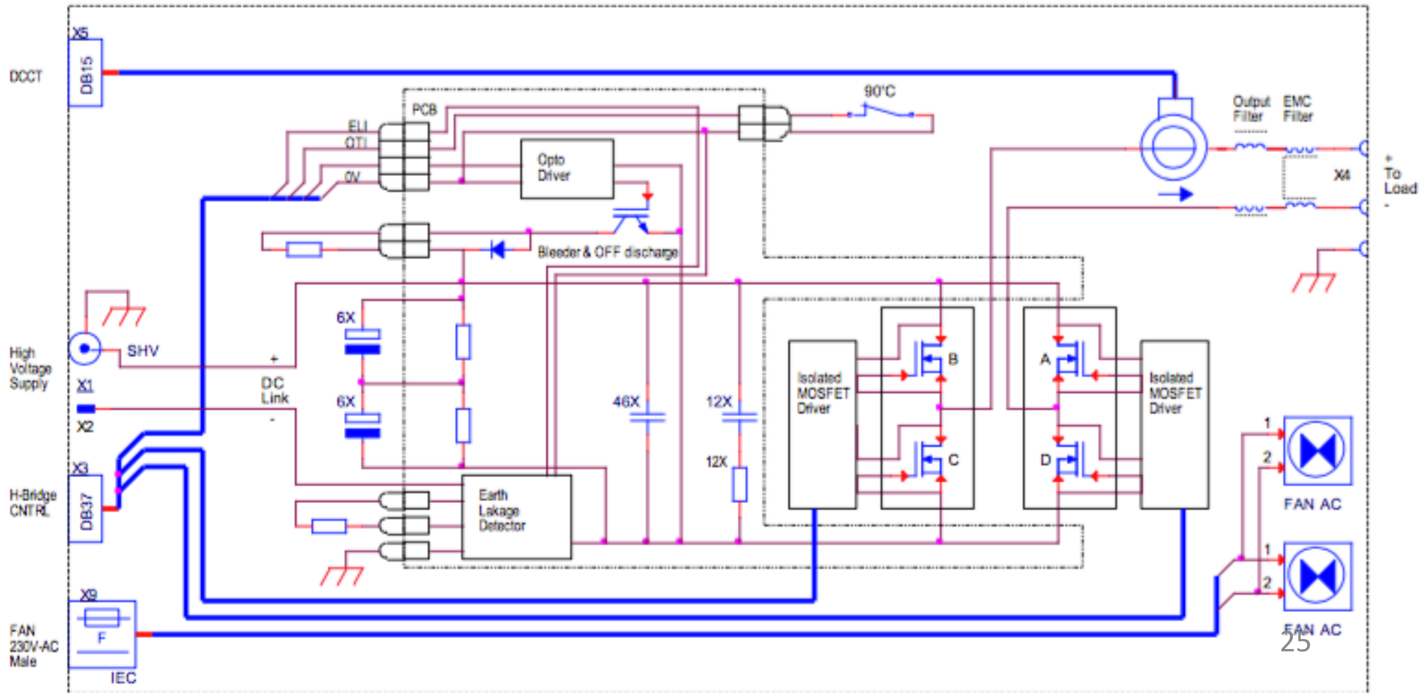



Input Converter (Capacitor Charge PS)
Line In
230V L,N,PE
AIO
HV
Output Converter
HV - X1, X2
+
X4
-
DCCT - X5
H-Bridge - X3
Fan - X9
Control Crate
Fan - X9
H-Bridge - X4
DCCT - X5
Inp.Cnv - X3
Polarity - ISO3
Sync.Frq. - ISO1
Pre Trig - ISO2
Trig Permit - ISO12
Beam Run Permit - ISO11
I-Ready - ISO14
Staus Present - ISO13
Interlocks - X1
Magnet Temperature
Spare
Remote Control - X2
X7 - B-Dot Out
Line In - X8
230V L,N,PE
B-Dot In - X6
Cable Matching Filter
LOAD
To Other RSMS-PS
X
Y
X
Y
X
Y
X
Y
IN
Polarity Controller
OUT
UNIVO
Light guide Control Signals
LAN#1
LAN#2
LAN#3
LAN#4
LAN#5
LAN#6
LAN#7
LAN#8
MOXA
LAN
230V L,N,PE

RSMS-MPS

Output Converter, 19” 4U

- Cap. bank (and bleeder circuit)
- 2 x half-bridge modules: SiC MOSFET, 1.2 kV, 3.6 mΩ (CAS325M12HM2)
- Gate drivers
- Output current transducer (for regulation)
- Heat sink with NC thermal switches (supply interlock)
- Short to ground on output: soft earth connection



Control Module, 19” 3U

- Central CPU module
  - Communication to local and remote control
  - Interlock supervision
  - ON/OFF control
  - Analogue measurements
  - Motherboard for regulation and DCCT module
- Signal interface module (including light guides)
  - Timing EVR
- Serial communication
  - 8-port MOXA for RS422-to-LAN
- DCCT interface
- Auxiliary power supplies for all electronics

Regulation

Intra-Burst (“fast”)

- Pos. and neg. current peak levels are compared for every “pulse”, e.g. every 1/40 kHz
- A waveform DC offset can be neutralized in time domain: by introducing a timing skew in the H-bridge

Inter-Burst (“slow”)

- Pos. and neg. peak levels are averaged over a burst
- Levels are compared to amplitude setpoints
  - Predicted DC Link value is reconfigured in the post-processing phase.

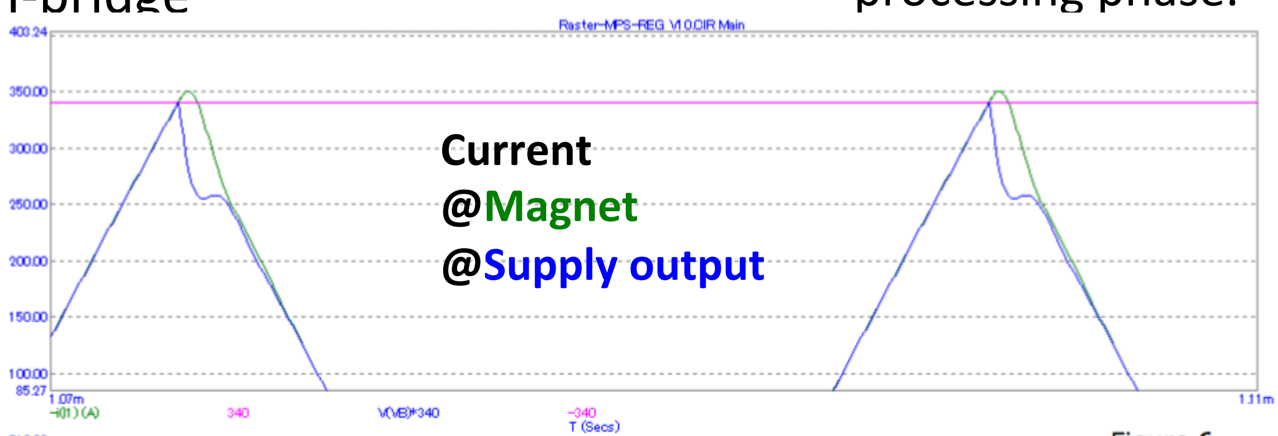


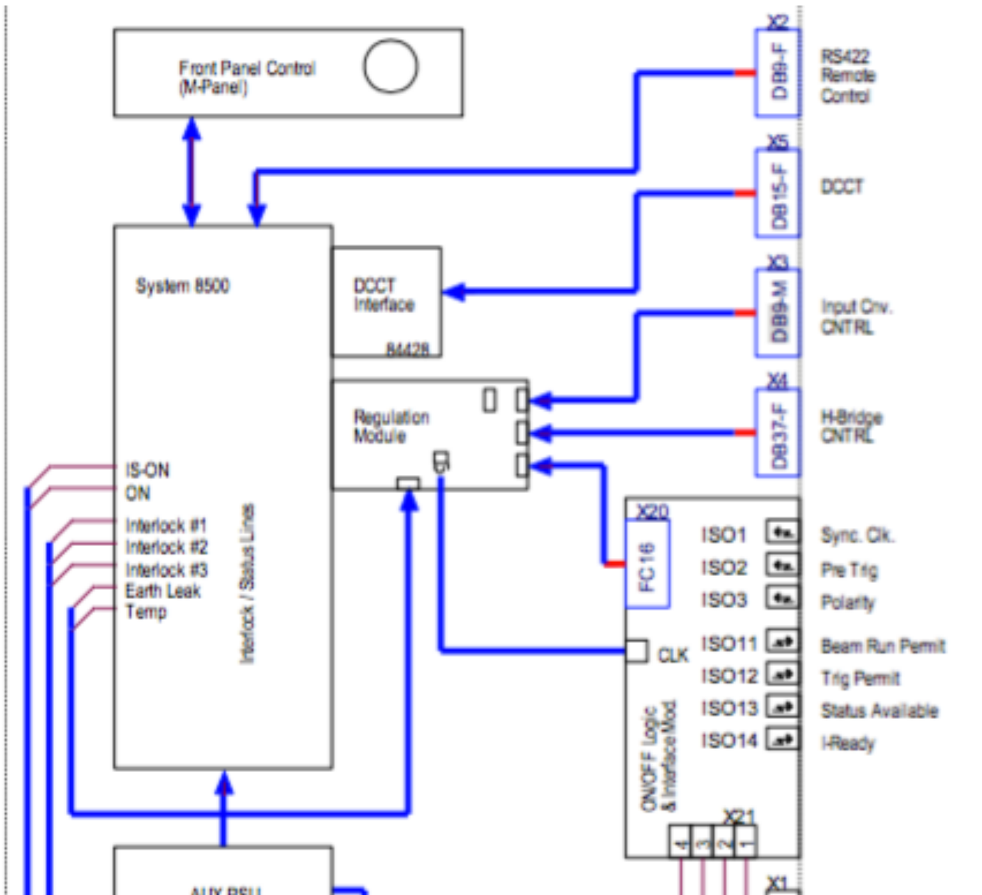
Figure 6

ICS

- Design has been closely discussed with ICS during the design phase.
  - Danfysik produced a Preliminary Design Report to settle interfaces with ESS systems, in particular ICS
  - ICS encouraged Danfysik to propose a working solution in terms of interfaces to ICS
  - Danfysik adopted the ESS standard optical transmitter/receiver
- System 8500 simulator + EPICS IOC is being implemented (Han Lee)
  - Several documents have been shared about the system
- The FDU is yet not at the stage of a physical design
  - Multiple hardware signals are made available at the RSMPS to the FDU

System Interfaces

- Apart from mechanical interfaces, RSMS has interfaces with
  - Timing system EVR: Pre-Trigger, external clock (light guides)
  - ICS: configuration, status readback (MOXA)
  - FDU: Bdot signals etc. (BNC)
- Several hardware signals are readily available for monitoring the system state on a fast time scale



Synchronization

Pre-Trig & Reference Clocks

- Pre-Trig will be used to passively synchronize the respective wfms by the assumption that
  - the 8 x Pre-Trig signals are received synchronous
  - the specified usable 3.57 ms raster burst is deterministic in terms of start and end relative to the Pre-Trig signals, independent of raster wfm frequency or other parameters.
- External clock (E-Clk, based on ESS MO) will be fanned out to supplies and used to generate raster wfm by decimating to 2x wfm frequency.
- If external clock is absent, RSMPS will revert to its internal clock (I-Clk, at 88 MHz or 44 MHz?)
  - internal clocks are not individually phase-locked
  - internal clocks are not phase-locked to external clock
    - may result in phase error ~1/f.IClk, 200 ns is tolerable on combined wfm
  - The 8x I-Clks are bought to have very similar absolute frequencies.

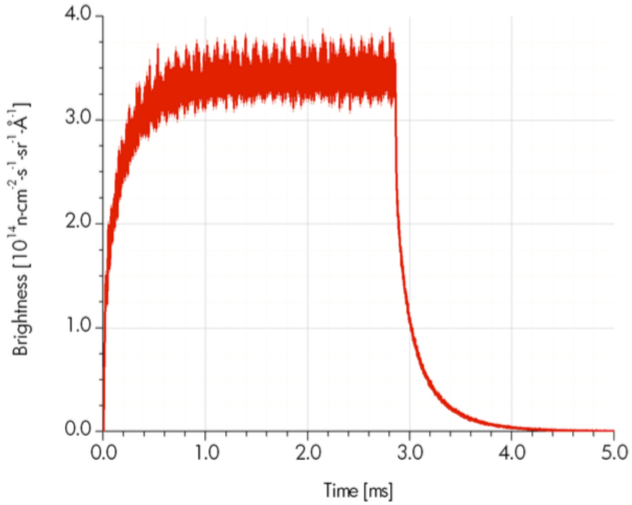
Clock Failures?

Case: a single RSMPS loses its E-Clk

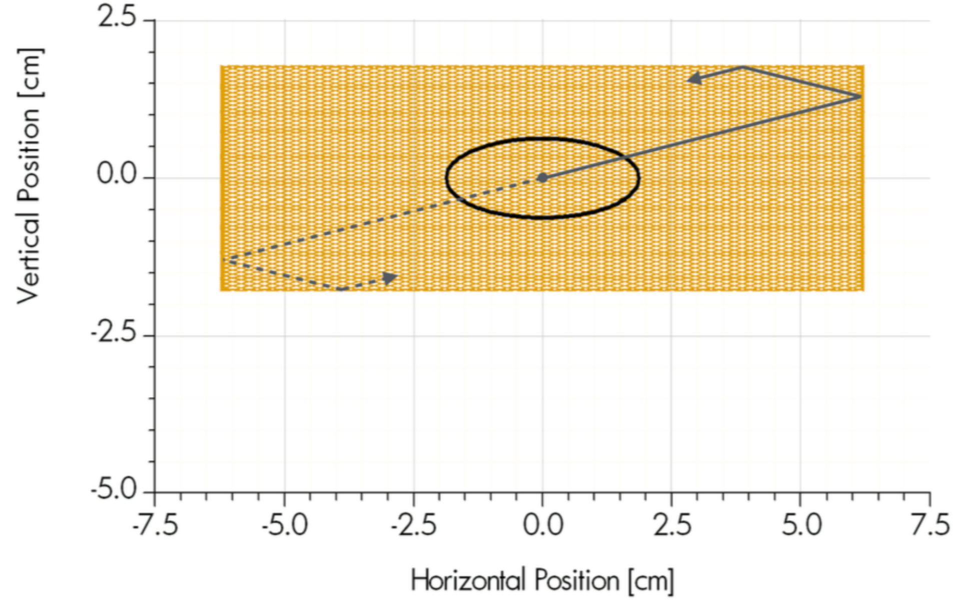
- *If only the affected RSMPS reverts to I-Clk,* differences in frequency of I-Clk and E-Clk will be visible over the course of a single burst
  - reduced combined wfm amplitude + less sharp peak
- *If all supplies revert to their respective I-Clk,* some way of mediating this should be foreseen.
  - Active signal from FDU to make all supplies revert to I-Clks?

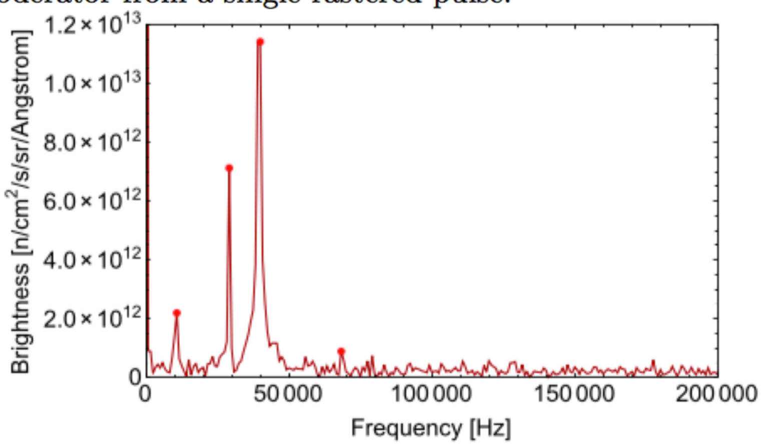
Raster Pulse: Alternating Parity

Shea et al, ICANS'15

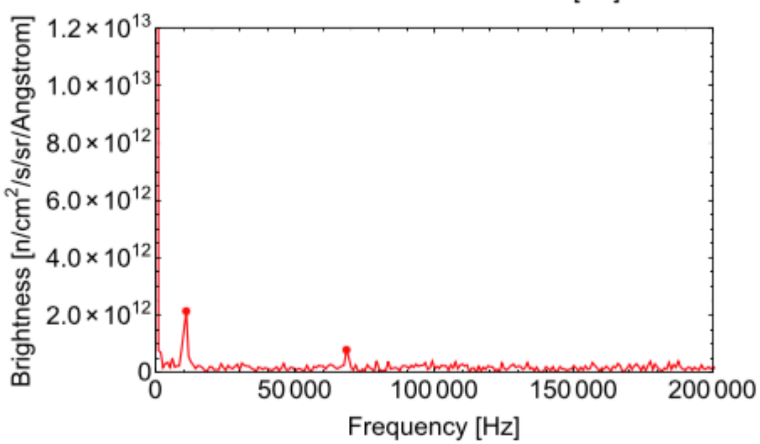


(a) 0.8 Å neutron pulse produced by thermal moderator from a single rastered pulse.



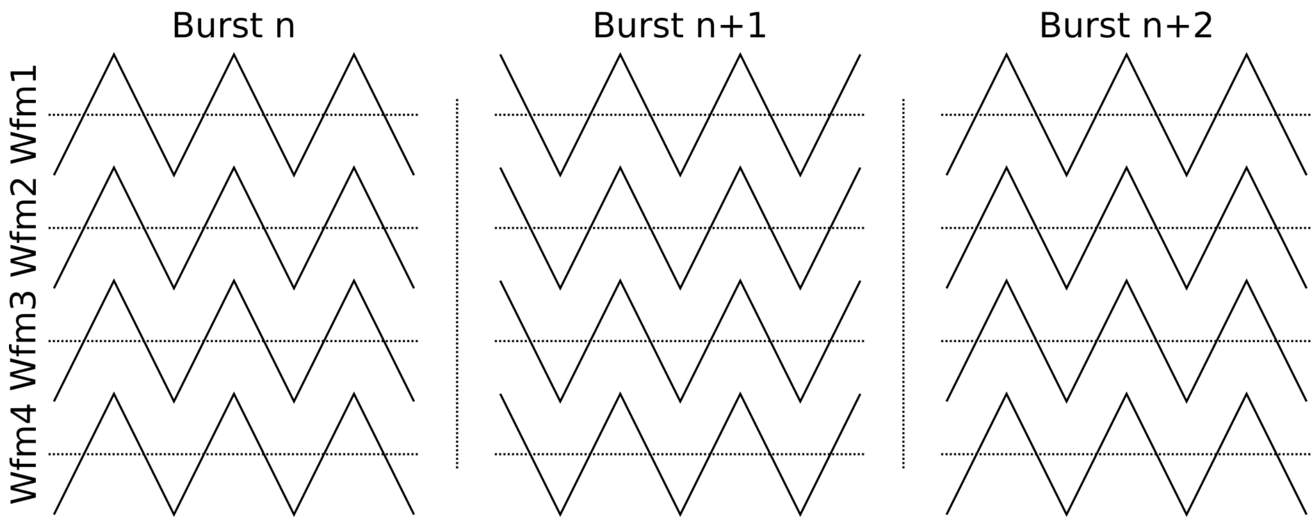


(a) From single neutron pulse.



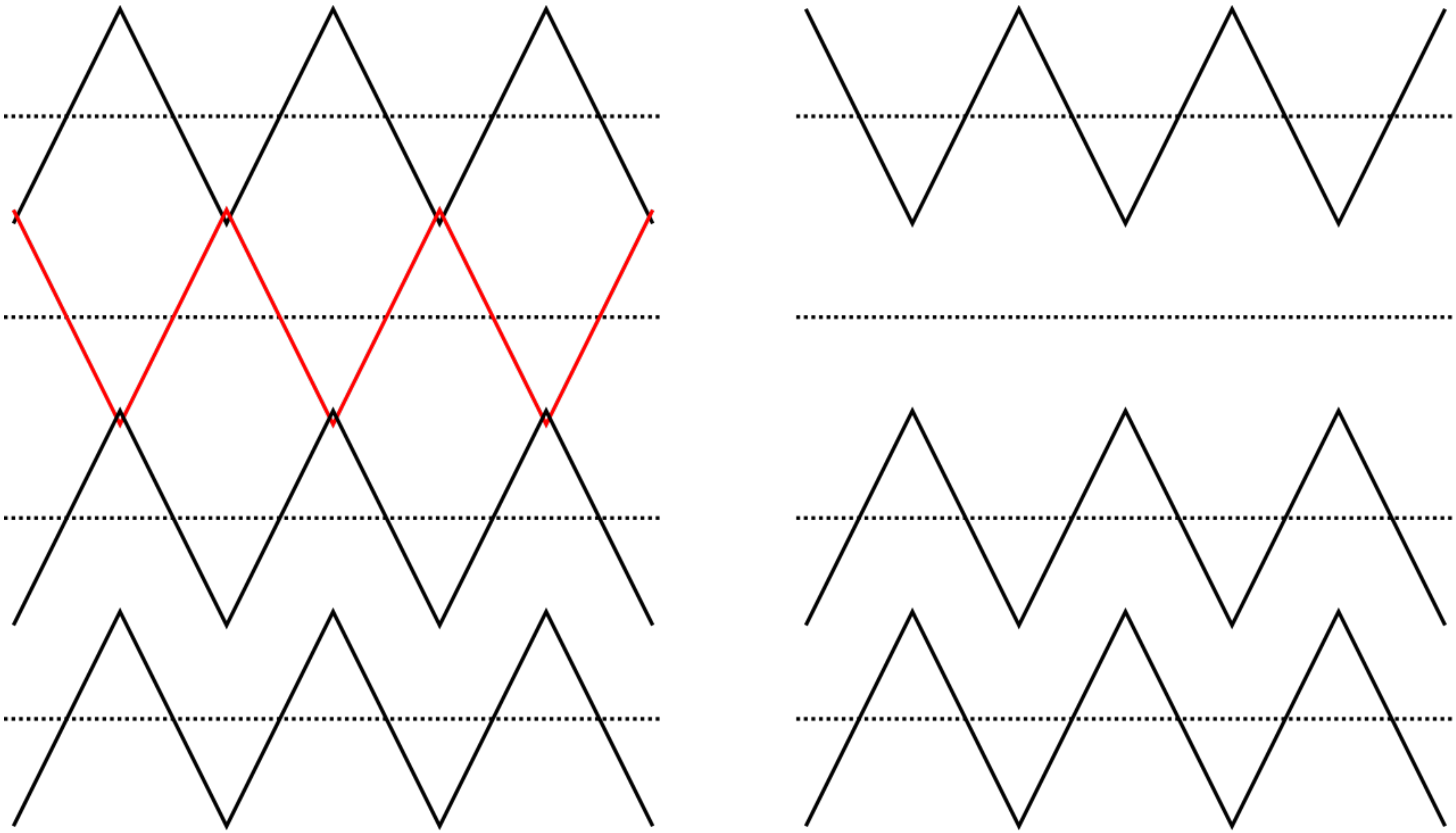
(b) From average over direct and inverted pulse.

Polarity Sync. of Waveforms (Wfms)



- The wfm polarity is to alternate with burst (beam pulse) number (neutron quality issue)
- Critical to sync. polarity within e.g. 4x H RSMs
  - Could lead to wfm cancellation
  - Implementation of polarity sync. could determine impact of faults

Polarity Sync. of Waveforms: Faults

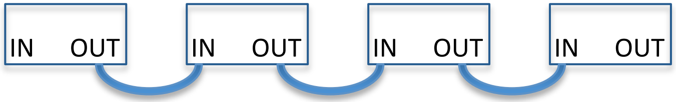


Isolated pol. failure -> 50% amplitude

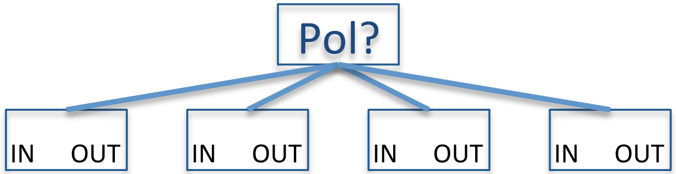
Serial * polarity failure -> 25% amplitude

Polarity Sync. of Waveforms: Implementation?

- Internal: simple counter, reset upon configuration
  - Hard-coded into supplies
- Serial: head of chain will be master
  - If the chain is broken several masters could be present



- Parallel: all units are similar (no master RSMPS)
  - External polarity master
  - High signal = Start positive
  - Frequency above 10kHz = Start negative
  - Low/No signal = Start negative, set the warning signal



Conventional Hazards

- High voltage cables: ±340 A, ±650 V (pulsed)
  - Clear labeling and distinction between HV and signal cables
  - Enclosing covers, only removable by tools

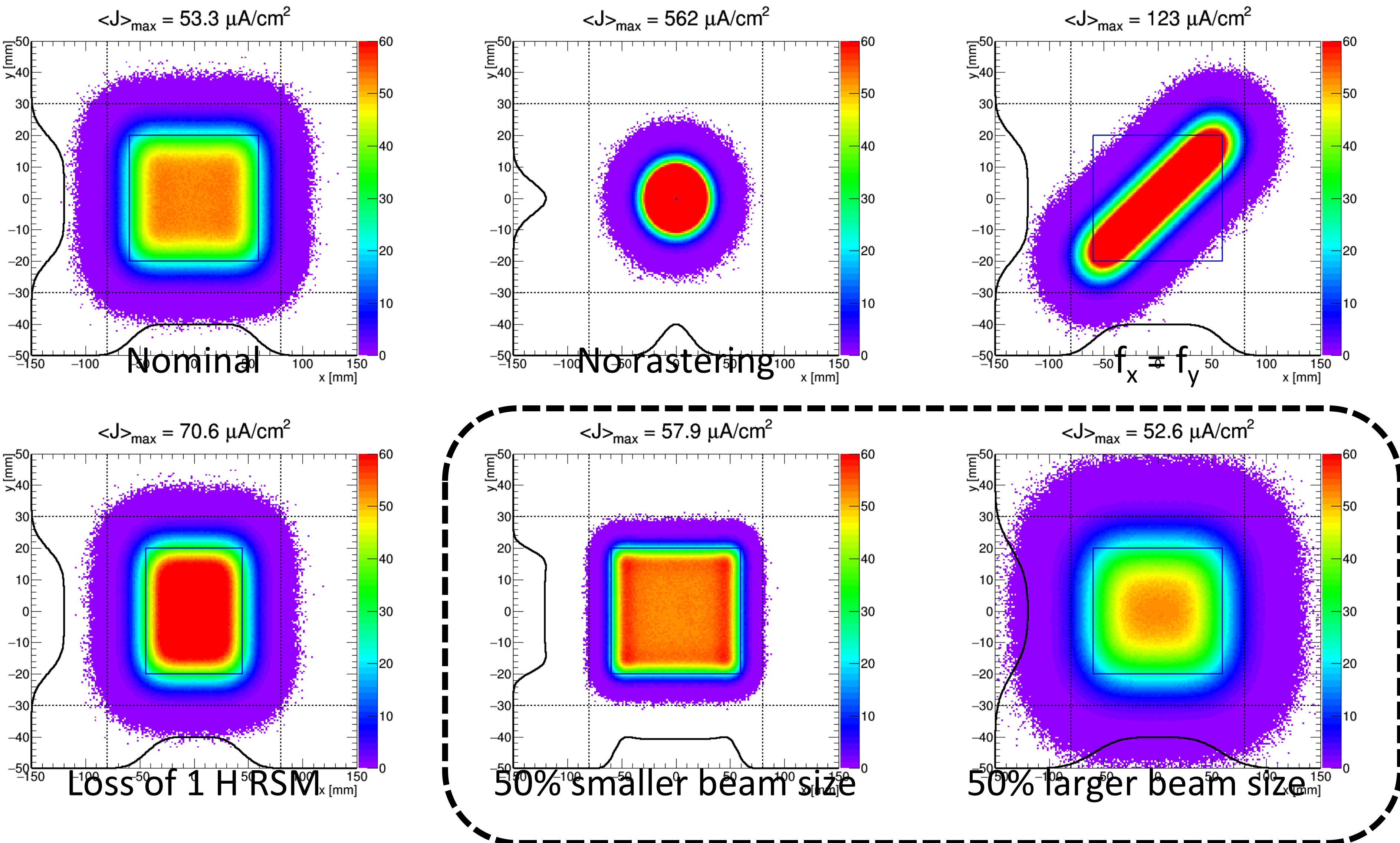
- Mechanical hazards:
  - Topple dangers should be avoided if possible
  - Girder should be secured in place once aligned
  - Common practice in accelerators

RSM Failure?

EUROPEAN SPALLATION SOURCE

Figure of merit:

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



RAMI

Incident	Type	Occurence	Impact	Time to recover	Preventive measures
1 x power supply failure	Random	< 1 / y	Not harmful for short periods	< 10 min. by adjusting the remaining 3 RSMs.	Monitor internal operating temperatures
8 x power supply failure	Random, common mode (central system failure, configuration)	?	Single pulse: not harmful	< 10 min. depending on cause	High degree of parallel redundancy, monitor beam (PBI) and magnets (FDU) closely
			Multiple pulses: PBW / target failure	1-6 months?	
Cable, coil insulation deterioration	Lifetime	1 / 5-10 y?	Not harmful, assuming a localized sudden event	Tunnel access + minutes	Regular inspection for embrittlement
Vacuum leak	Random (following replacements, alignment)	?	Could prevent operation (beam loss on res. gas)	1-2 days depending on cool down time and preparation	Monitor pressure near raster section

- Redundant system of raster magnets with strength contingency allows for a quick recovery
- The design aims at using radiation-resistant materials, where possible. Additionally components, like cables, are placed as far away from the beam center and prepared for swift replacement.

Suggested Spare Components

Part	Quantity	Comment
Cable between connection box and bus bars	32	Cables may be exposed to radiation causing degradation. The cables are easily exchangeable causing minimum down time.
Coils	2	May be exchanged in case of long term degradation of insulation
Ferrites, horizontal	2	Ferrites do not degrade. Ferrites are fragile and could potentially be damaged during exchange of a coil
Ferrites, vertical	2	As above
Vacuum chamber A	1	NB: Vacuum chambers could come with only a single QCF-100 flange -> 1 spare part type
Vacuum chamber B	1	

Verification

FAT I (pre-series), Supplier

- Mechanical, electrical, vacuum
- Magnetics: Performance ($B(t)$ waveforms, field quality, synchronization) of magnets + cable + supplies
- Validation program suggested by supplier – to be approved by Aarhus University (and ESS)

SAT I (pre-series), Aarhus University

- Visual inspection for potential shipping damage
- System installation + nominal performance testing

Performance Acceptance Test (pre-series), Aarhus University

- Operation will be assessed in detail and long-term stability tests will be made (<4+6 months)
- Typical operation modes + stress tests. Temperature readings (thermocouples + thermography)

FAT II (production series), Supplier

- As FAT I + additional points based on findings from pre-series PAT?

SAT II (production series), ESS + Aarhus University

- System installation + nominal performance testing

Top risks

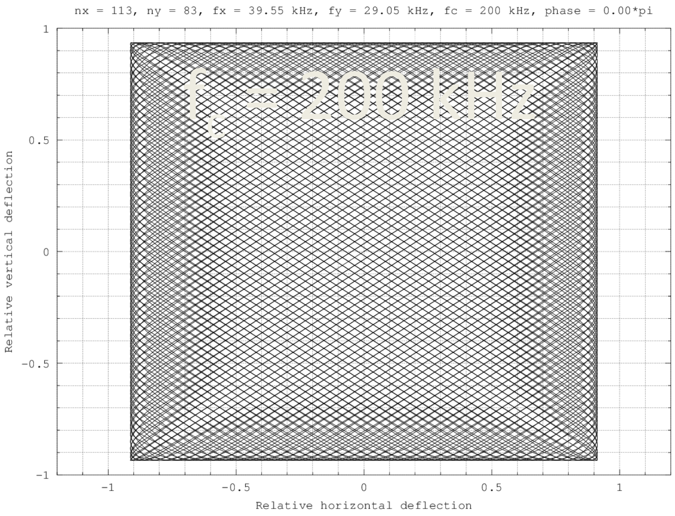
- Top risks
  - Late changes in design parameters: max *f* (neutronics), etc.
  - Unexpected effects and parameters not included in simulations:
    - cable, stray fields inducing eddy currents, etc.
    - Beam losses, activation due to backstreaming radiation from target
  - System not performing well under long-term tests (true & false trips)
- Planned risk treatment activities:
  - ✓ Perform cable tests before design phase is finalized
  - Pre-series!
  - MPS discussions: Include designer as early as possible

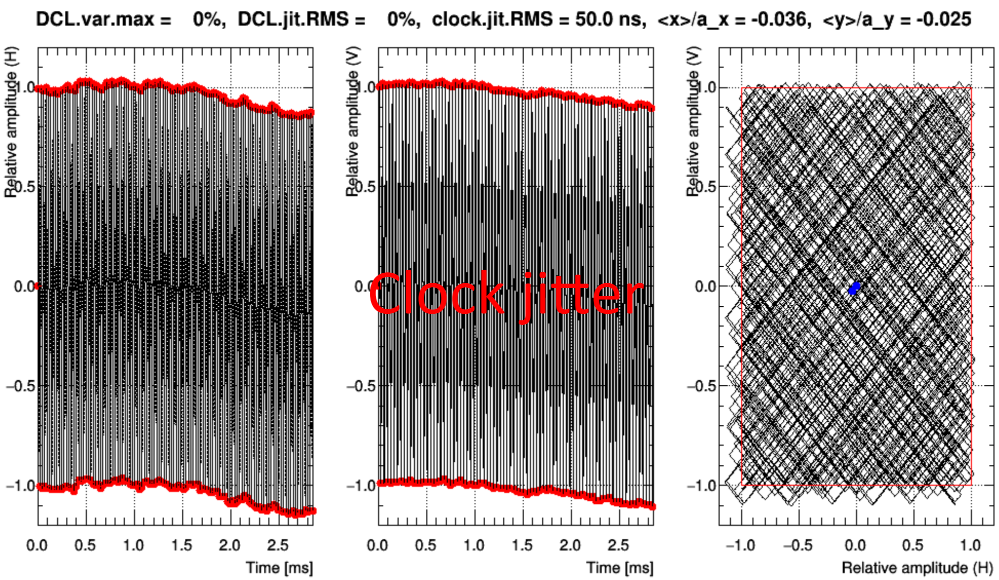
Thank you for your preparation, attention, and comments!

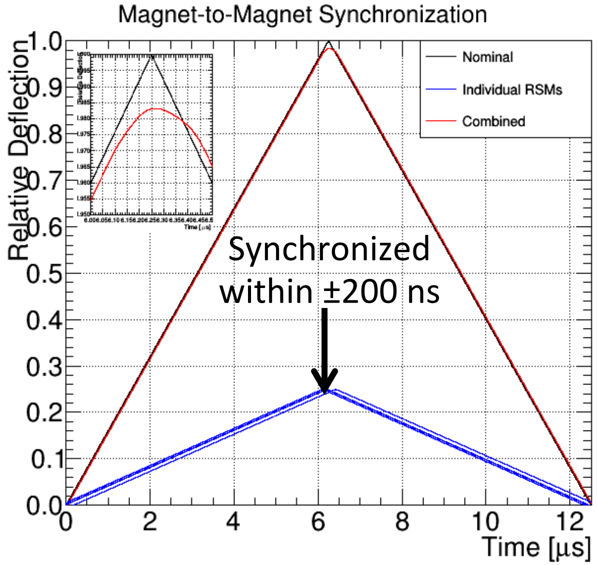
Extra Slides

Requirements

- Alignment, cable length, max. B.rho, …
- Frequency stability, bandwidth, waveform synchronization (M2M, H2V, R2B)
- Imperfections -> specifications:
  - $I_m(t) \sim \int dt.[V_{m0}(t) + V_{err}(t)]$
    - Ref. clock phase noise
    - V_{DCL}: Sets slope between switching. Switch-to-switch noise + function of time?







Integration and Verification

Interfaces:

- The subsystem will be complete / stand-alone -> interface points are few and typically clearly located
- Interfaces include:
  - Global control system, timing system, fast beam interlock (FBI, MPS)
  - Alignment, vacuum, el. power, (passively cooled pulsed system)

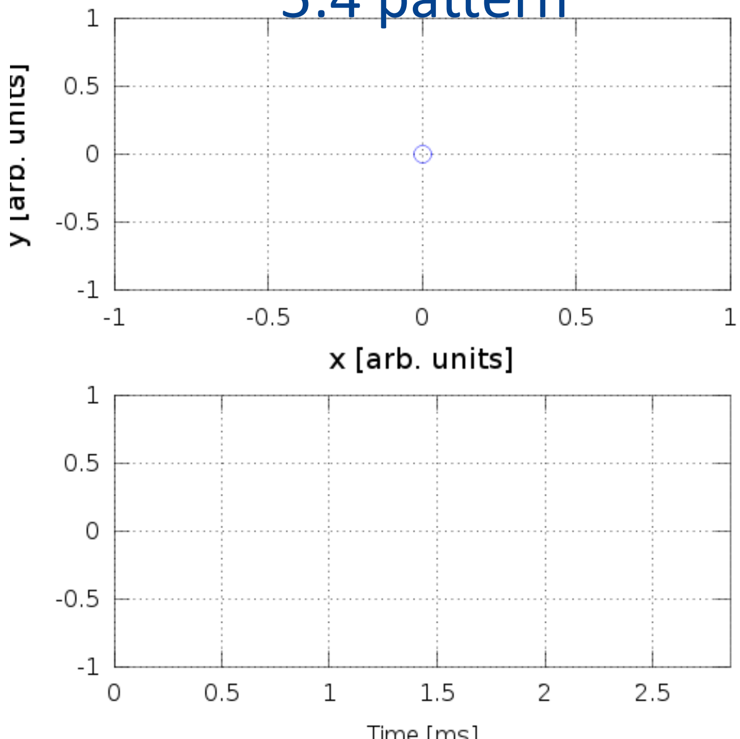
- 2015.03.03: Initial meeting on interface with FBI
- Preliminary mechanical sketch of system is being distributed

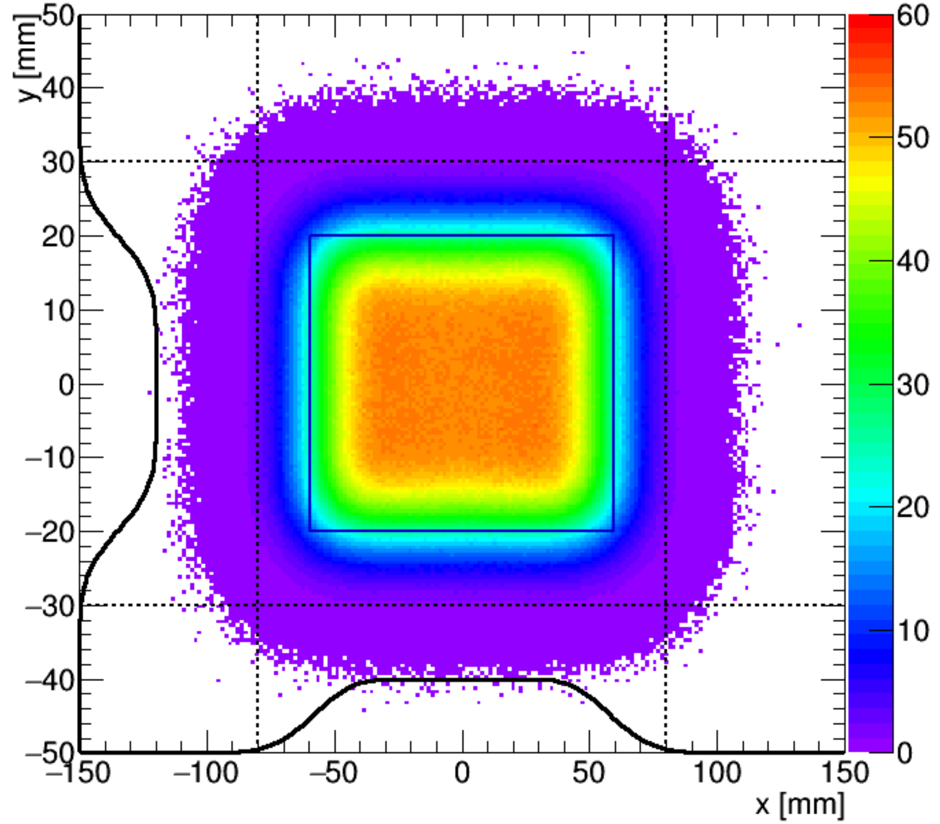
BDS Optics Design

BDS Overview

- Raster system sweeping beam in 2D pattern @ target
- 8 colinear magnets, individually powered
- Crosshatch pattern (f_x/f_y, ϕ_{xy}, a_x, a_y) within 2.86 ms pulse

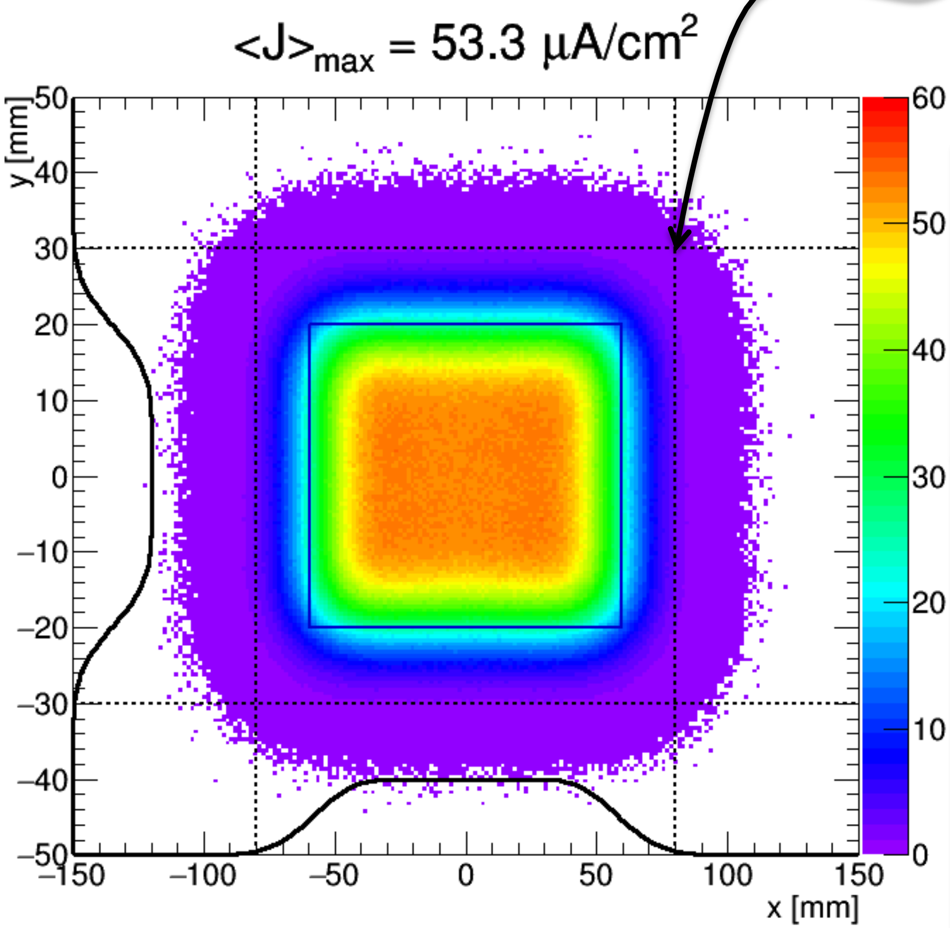
5:4 pattern





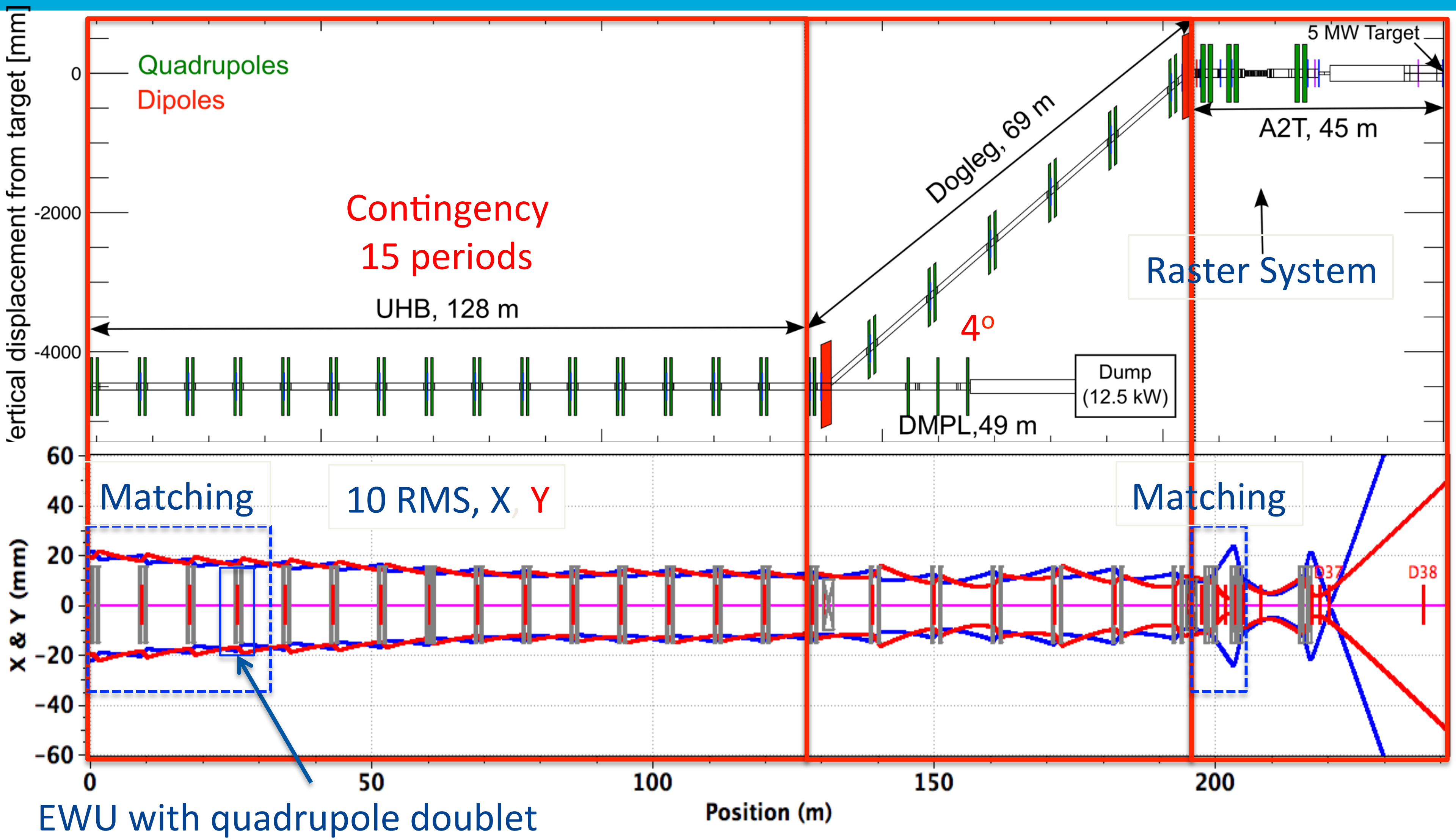
Requirements: Beam

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

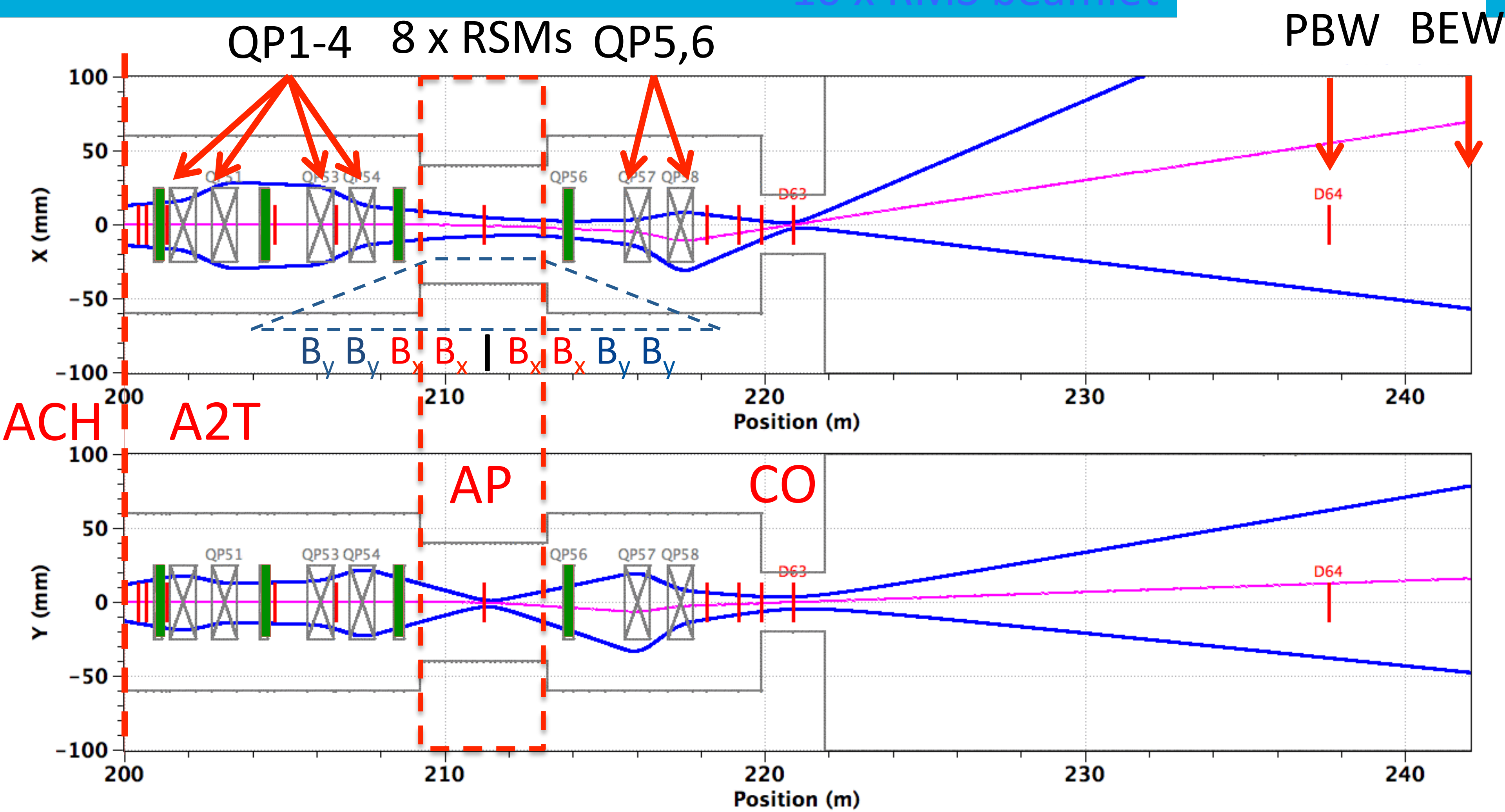


Group	Unit \ Location		PBW	BEW (Target)
d.o.f.	amp. x	mm	47.1	**59.5**
d.o.f.	amp. y	mm	15.8	**20.0**
d.o.f.	rms (x)	mm	10.7	**13.5**
d.o.f.	rms (y)	mm	4.10	**5.05**
requirements	rms(x)*rms(y)	mm^2	>44	>68
requirements	Jmax	uA/cm^2	---	<56
requirements	*p* outside 160x60	%	<1	<1
requirements	*p* outside 180x64	%		<0.1
requirements	*p* outside 180x62	%	<0.1	
requirements	Max. displacement	mm		± 5 (H) ±3 (V)
requirements	H raster freq.	kHz	>= 35	

HEBT Layout & Beam Optics

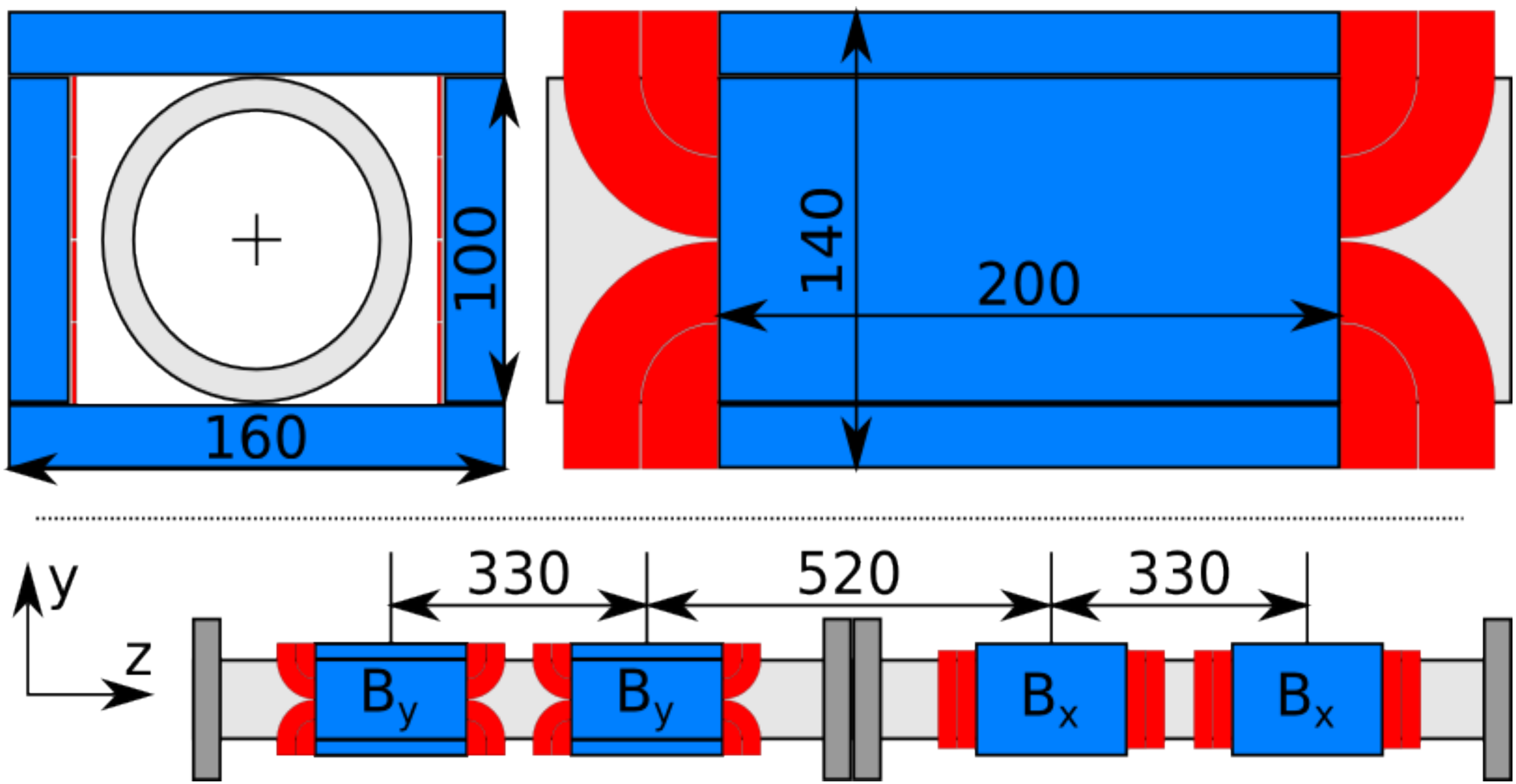


A2T Beam Optics

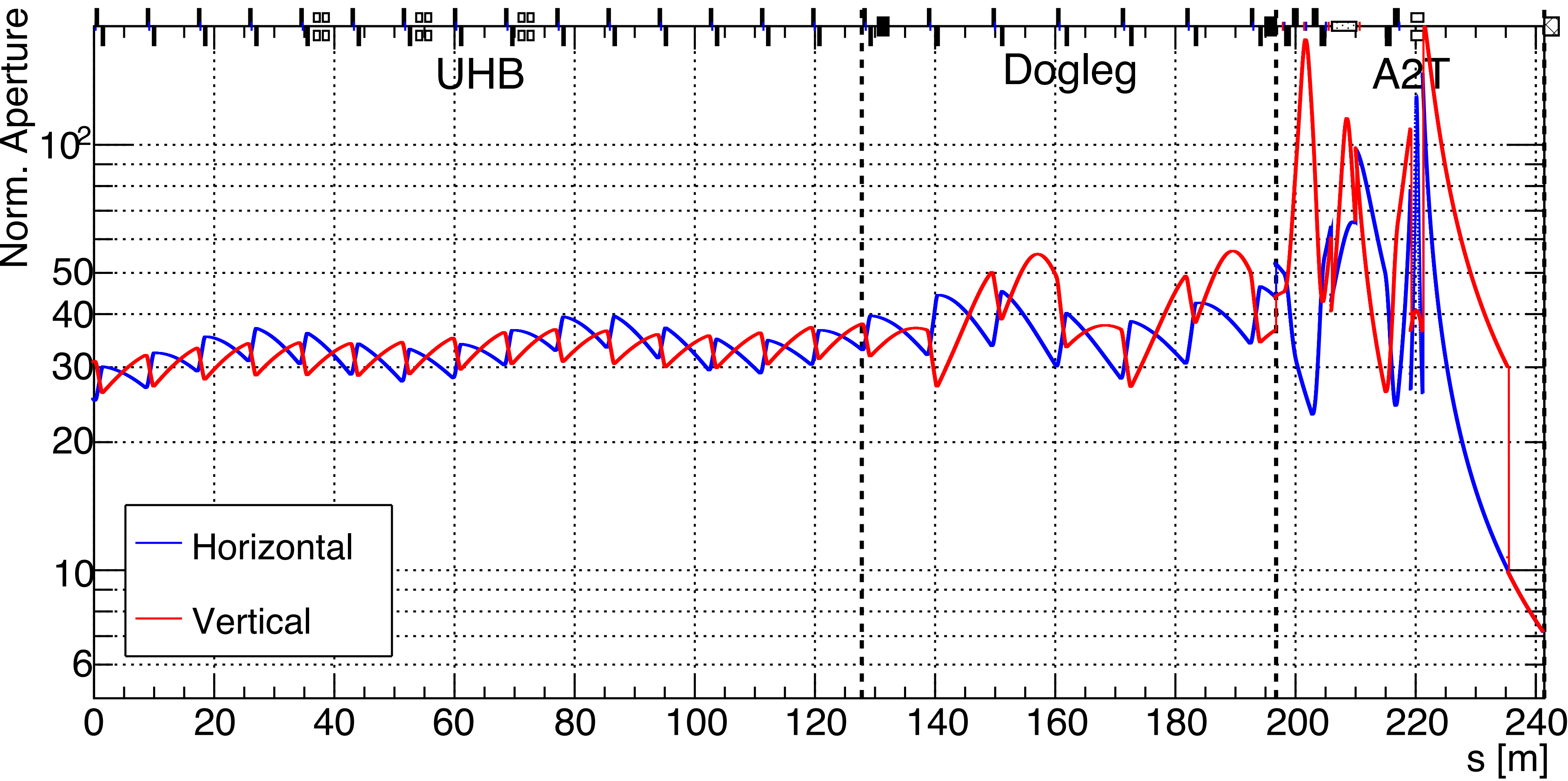


2.0 GeV: B_xL = ±2.6 mT.m, B_yL = ±1.5 mT.m, ±5 mT.m

Raster Magnet Hardware and Layout

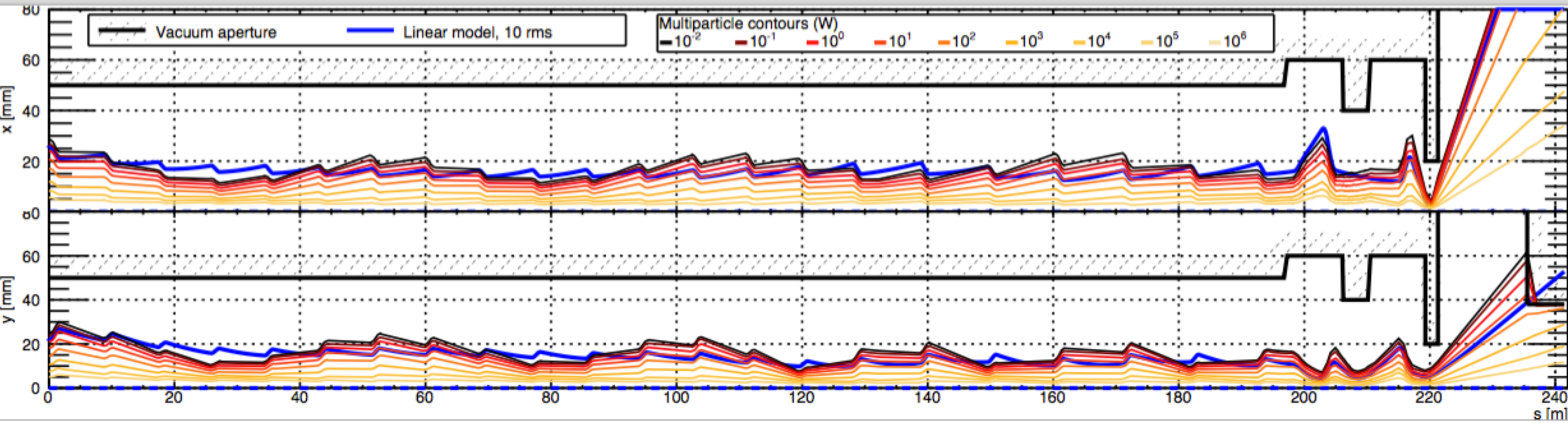


Normalized Aperture



IPAC'14, WEPRO073

Multiparticle Studies



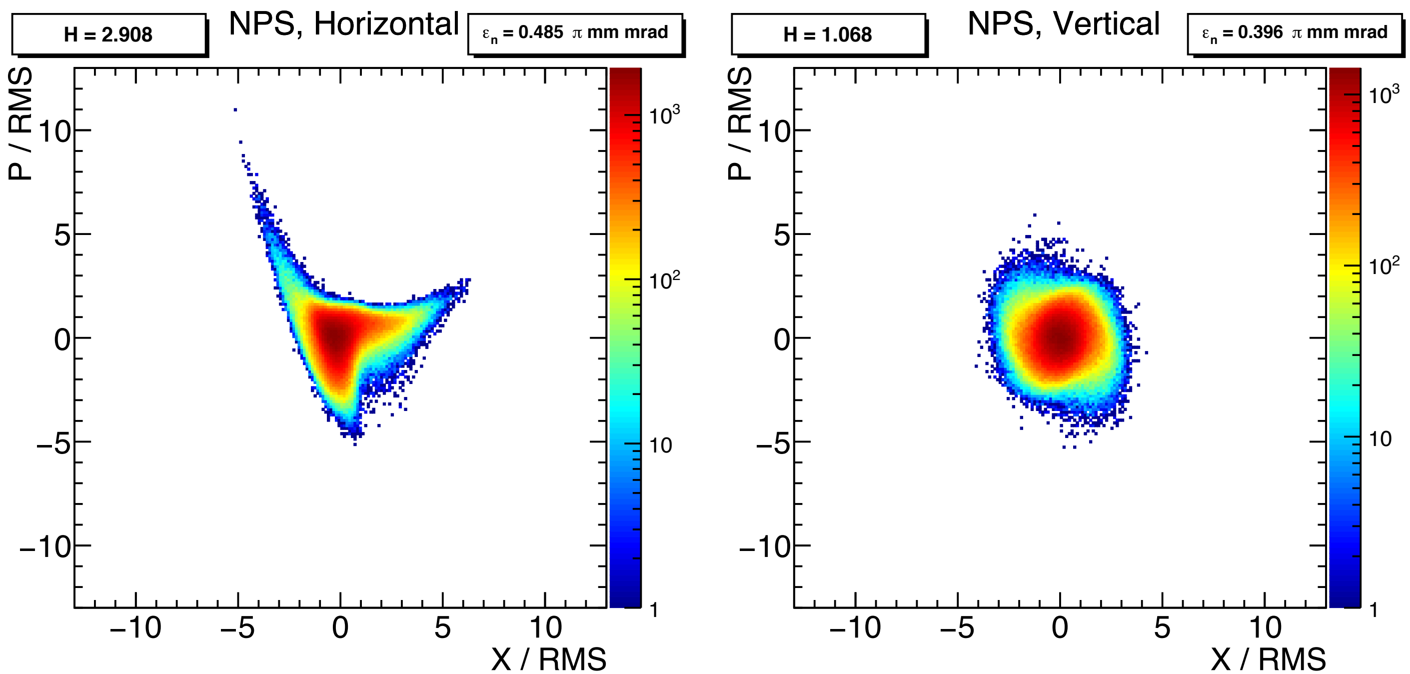
- 1000 HEBTs x 10^6 particles
- RSM aperture (*s* = 207 m) appears adequate
- NSW aperture (*s* = 220 m) appears adequate

Element	Parameter	Unit	Static	Dynamic
Quadrupole	dx, dy	mm	0.2	0.01
	$d\hat{z}$	deg	0.03	0.003
	Gradient	%	0.5	0.02
Dipole	dx, dy	mm	0.2	0.01
	$d\hat{z}$	deg	0.03	0.003
	Strength	%	—	0.02
Beam	dx, dy	mm	2	0.25
	dx', dy'	mrad	0.1	0.01
	Energy	MeV	20	2.5
	Emittance	%	10	1
	Mismatch	%	10	1
	Current	mA	1	0.1

IPAC'14, WEPRO074

A2T Quadrupole Magnet Harmonics?

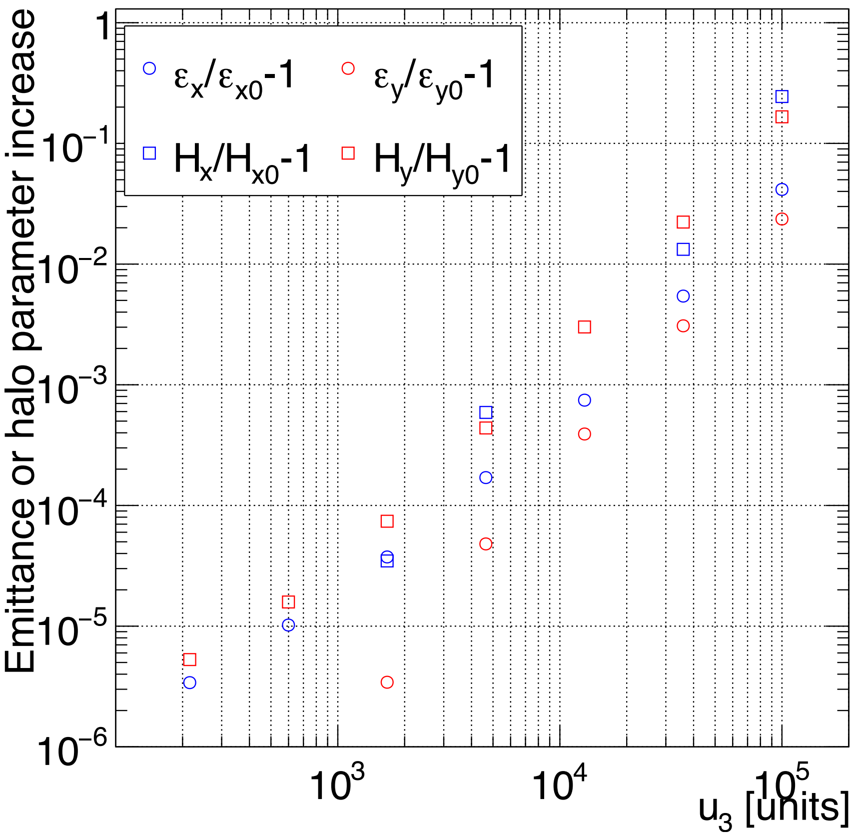
- A2T quad harmonics were scanned in log. steps 1 u to 100 u ($u_n = \int \Delta B_n/B0 \times 10^4 = 1$ u)
- 500 k particles tracked to target



7.7 unit contamination for each u_n

RSM Systematic Sextupole?

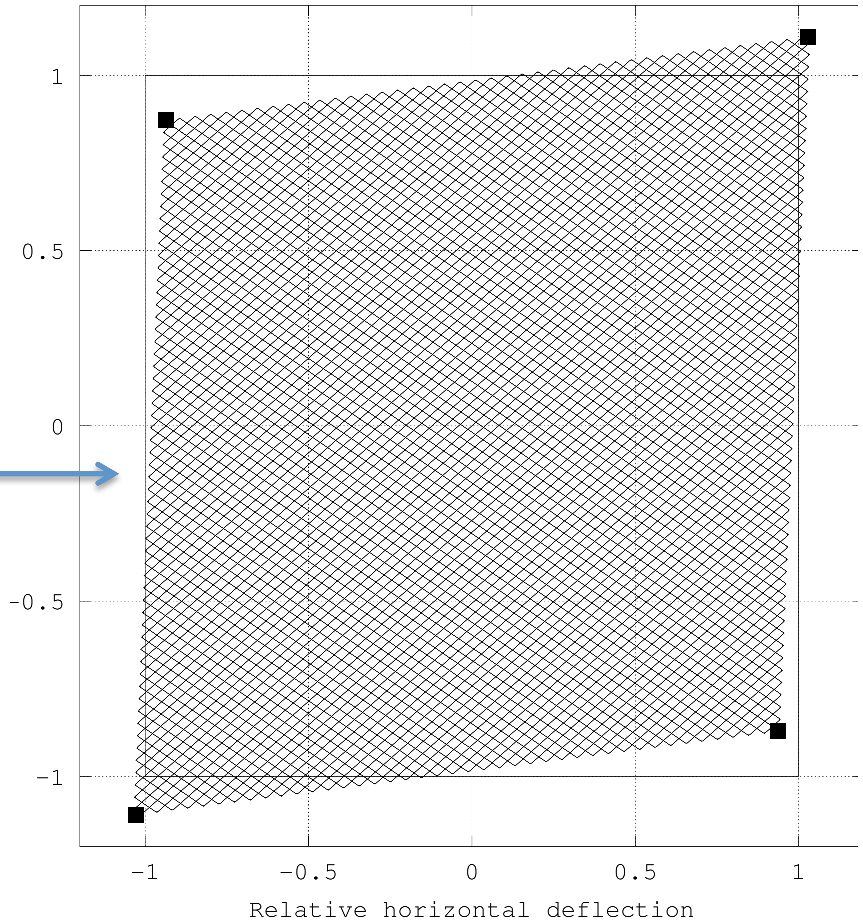
- $u_3 = \int \Delta B_3 / B_0(t) \times 10^4$
- Beam along RSMs:
  - rms size < 1 mm
  - dx, dy < 3 mm
- RSMs
  - GFR = ± 15 mm
  - Gap = ± 50 mm
  - Aperture = ± 40 mm
- RSM $u_3 < 10^3$ (or 10%)



Systematic sextupole (u_3) in H RSM set

RSM Alignment Errors?

- Insensitive to displacements:
  - dx, dy < 0.5 mm
  - dz < 0.3 mm
- Roll errors:
  - distorts pattern outline (shearing)
  - depends on average roll error in H/V set
  - pitch, yaw, roll < 1 mrad



Roll error distribution < 100 mrad