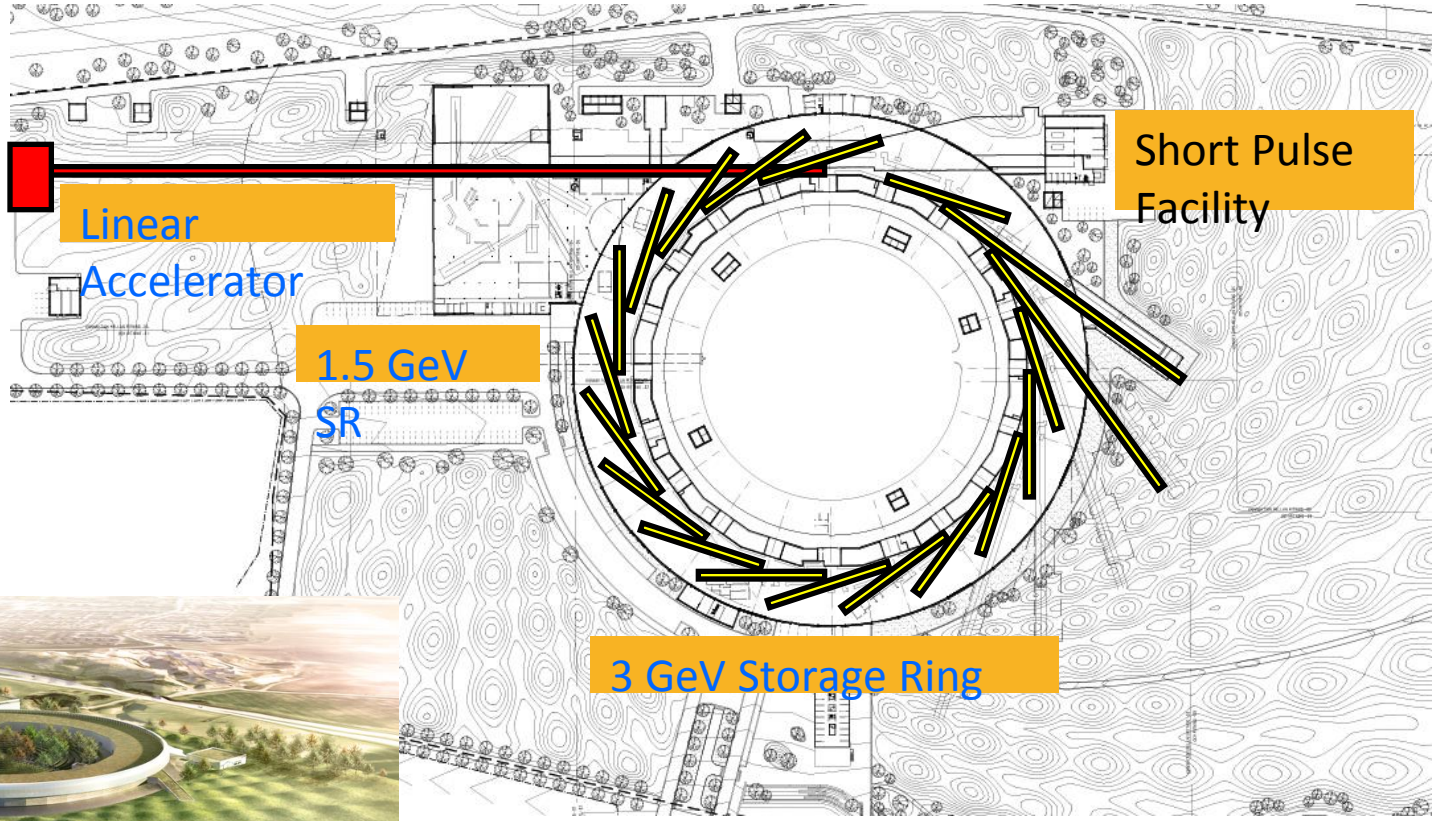
Status & commissioning of the MAX IV

Outline

- MAX IV overview
- MAX IV - Linac
- MAX IV - Ring RF system
- Ring RF – Cavities
- Ring RF – Power plants
- Digital low level RF
- Chopper for ring injection
- Commissioning

MAX IV overview

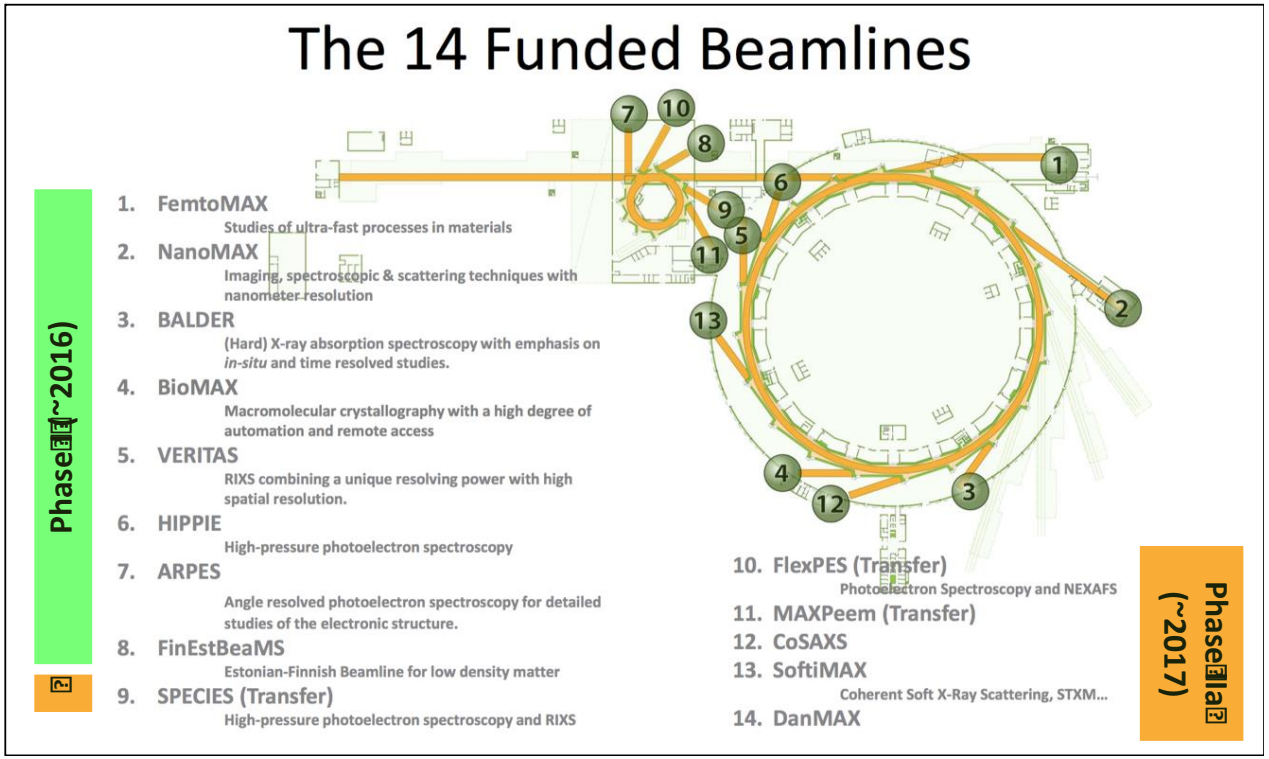


Inauguration was June 21, 2016

Annika Nyberg, MAX IV-laboratoriet, 2012

MAX IV Facility Overview

- Facility can accommodate up to 32 user beamlines: 3 @ SPF, 10 @ 1.5 GeV SR, 19 @ 3 GeV SR
- 14 have been funded in our first two beamline phases



MAX IV LABORATORY

Aerial View of the MAX IV Site

Photo Perry Nordeng

Where is MAX IV Laboratory?

Inside the Linac building

Klystron gallery

Photo Annika Nyberg

Linear accelerator

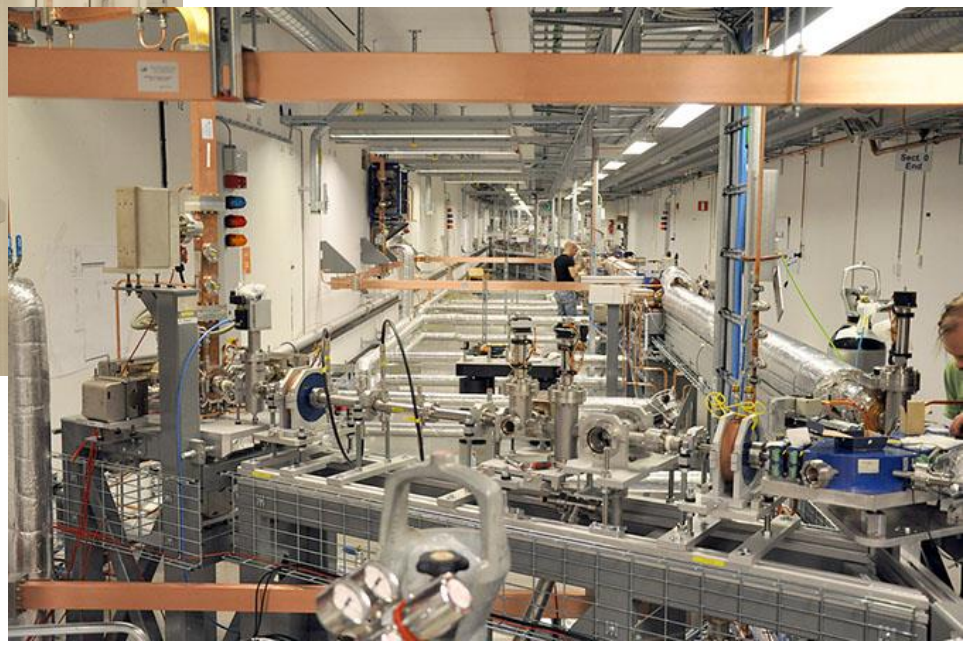


Photo Annika Nyberg

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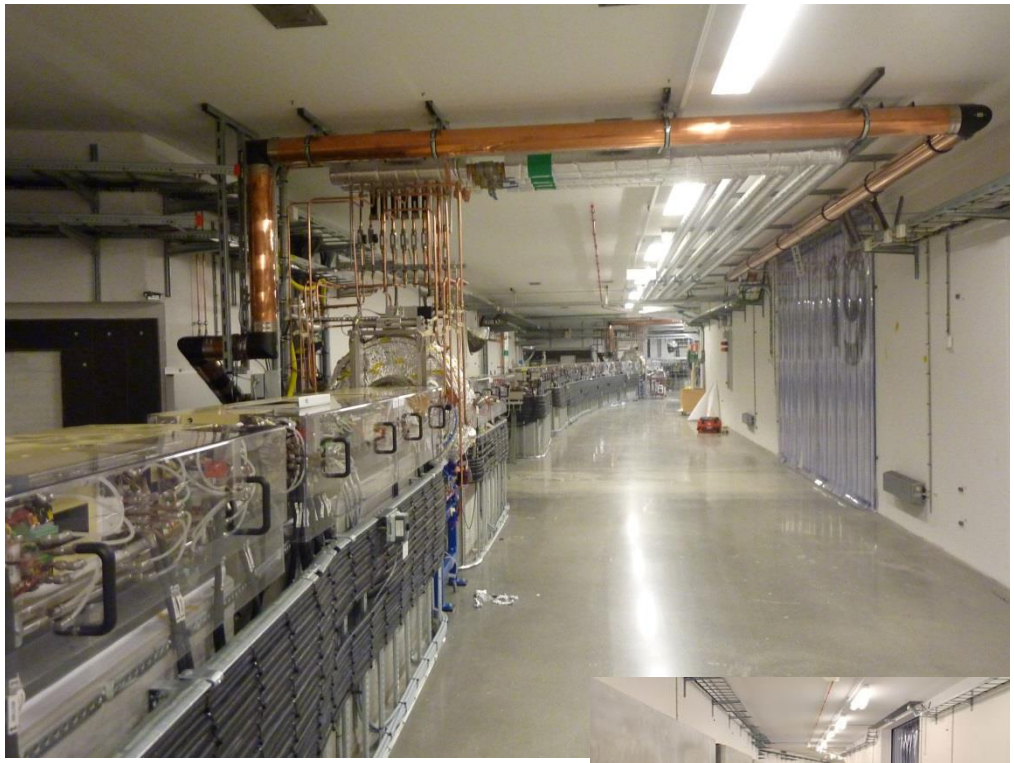
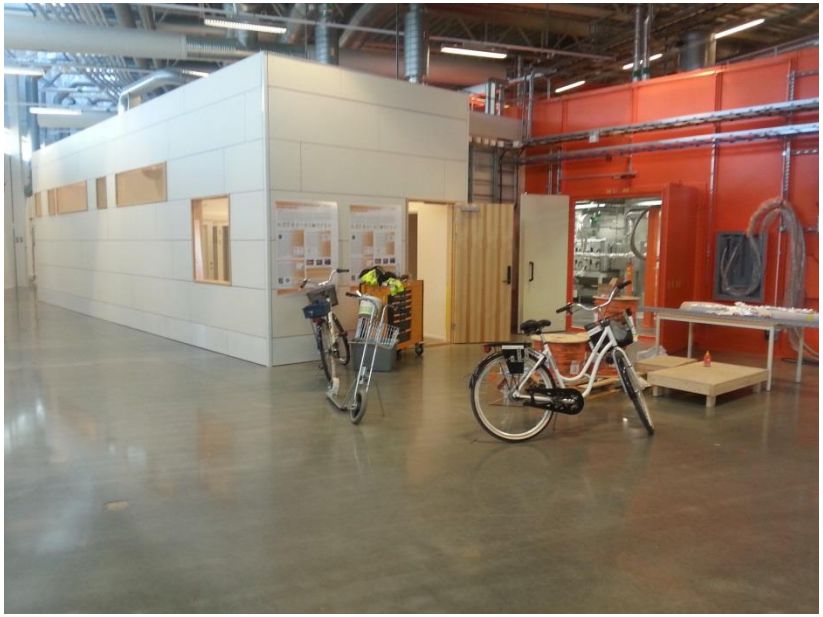
Inside the 3 GeV building



Ring tunnel, start of commissioning, September 2015.

Photo Annika Nyberg 140828



The experimental hall with one of the beamlines experimental hutches. Seven is already funded.

MAX IV Linac

The linac should be used as an injector for both the 1.5 and 3 GeV storage rings and the SPF (Short Pulse Facility)

- 18 klystrons
- 18 SLEDS
- 39 linac structures
  - Operating frequency 2998.5 MHz
  - Maximum rep. rate 100Hz
  - Maximum RF power 35 MW
  - RF pulse length 4.5µs
  - Linac length 250 m
- Two Electron sources
  1. One klystron (7.5MW) feeding a thermionic RF gun used for ring injections
  2. A photo cathode gun for the SPF fed from the first linac klystron

Operating beam energy 3 GeV
Max. on-crest beam energy 3.6 GeV

➡ 44% RF power redundancy. Part of this has been reduced due to arcing at some of the RF Power Units at high power. For safe operation two RF units will be added in May 2017. The linac tunnel is prepared for this change.

MAX IV linac - Conditioning

- RF conditioning did take longer time than anticipated despite that everything except the waveguides is preconditioned by RI. Problems with the subsystems have limited the time for conditioning
- 16 RF stations are fully conditioned
- Only minor impact on the Linac commissioning time schedule. The personal safety system PSS was changed so that it is possible to accelerate electrons up to the first bunch compressor while RF conditioning could continue in the rest of the linac.
- 3 GeV was reached for the first time February 9, 2015

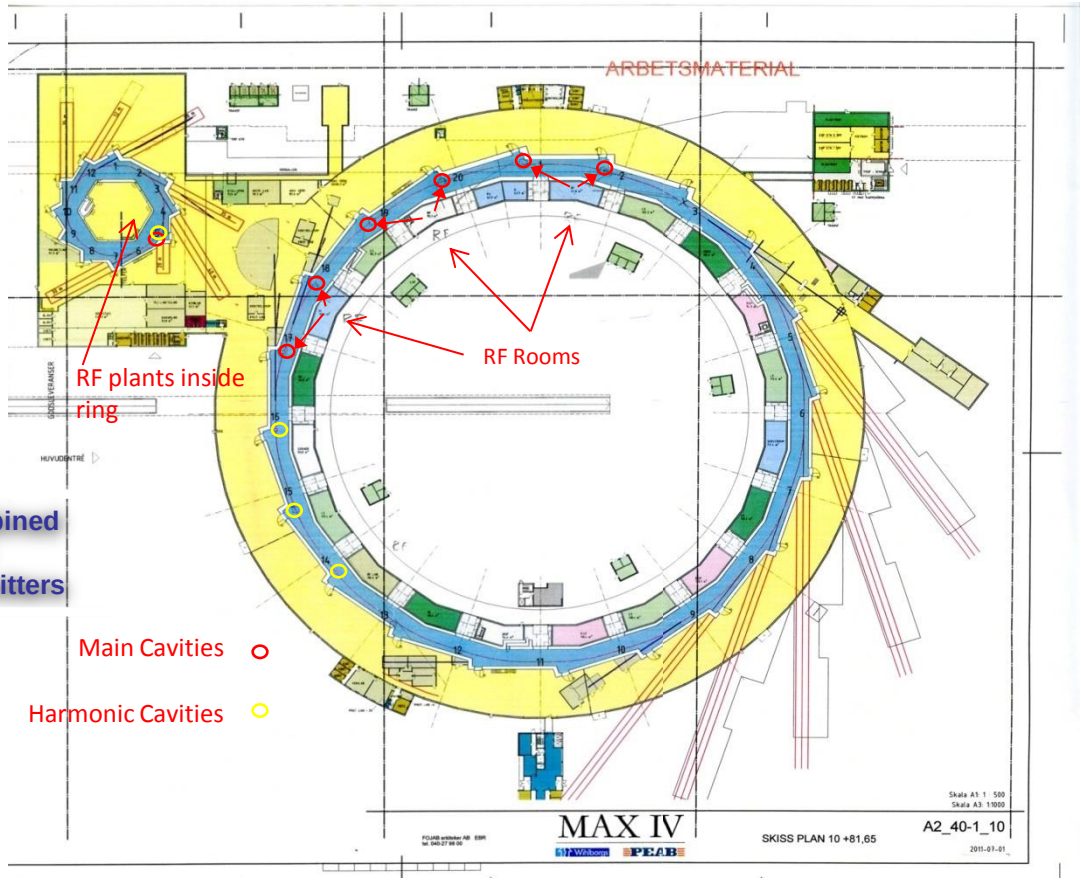
MAX IV Ring RF System

Storage Rings Parameters

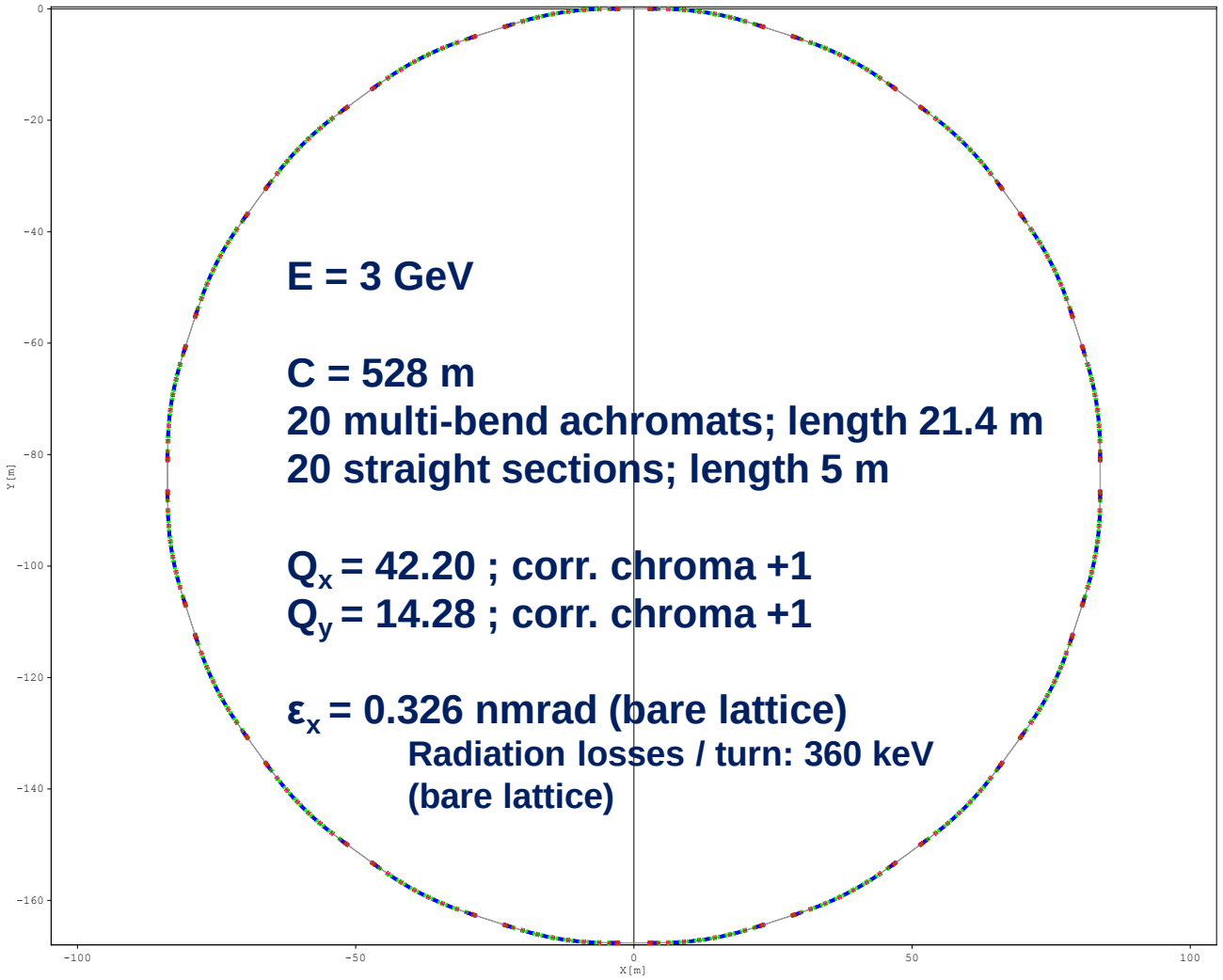
Energy	1.5 GeV	3.0 GeV
RF	99.931 MHz	99.931 MHz
Circumference	96 m	528 m
Harmonic number	32	176
Current	500 mA	500 mA
No of cavities	2	6
RF station power	60kW	120kW
Cavity voltage	280kV	300kV
Coupling (beta)	2.3	4.0

2 combined 60 kW transmitters

1 single 60 kW transmitters



MAX IV 3 GeV - Storage Ring



E = 3 GeV

C = 528 m
20 multi-bend achromats; length 21.4 m
20 straight sections; length 5 m

Q_x = 42.20 ; corr. chroma +1
Q_y = 14.28 ; corr. chroma +1

ε_x = 0.326 nmrad (bare lattice)
Radiation losses / turn: 360 keV (bare lattice)

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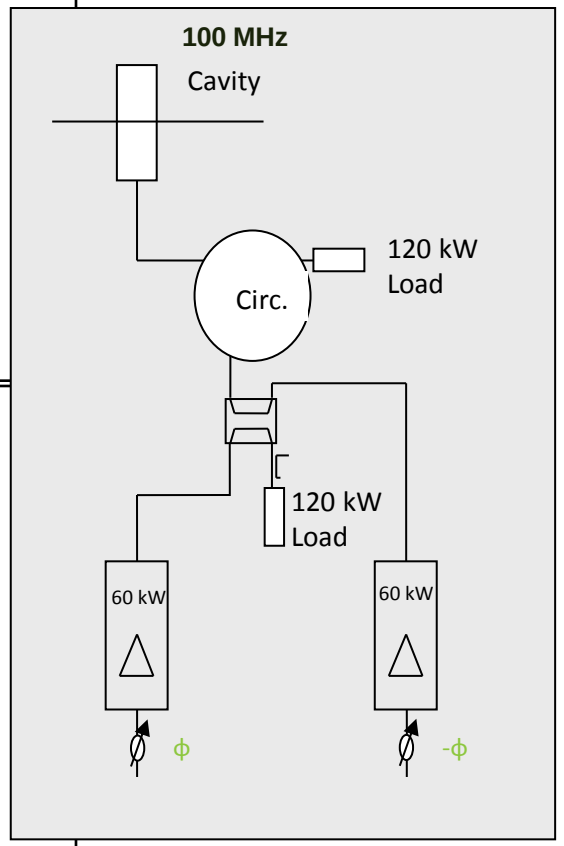
Ring RF System - 3 GeV Ring

Alternative	I	II
Energy loss with Ids	756keV	1020keV
Circulating current	0.5A	0.5A
Total beam power	378kW	510kW
Total RF voltage	1.5MV	1.8MV
Number of cavities	6	6
Cavity shunt impedance	3.2Mohm	3.2Mohm
Cu losses	117kW	169kW
Total RF power needed	495kW	679kW
Nr of RF stations	6	6
Nr of transmitters	12	12
Transmitter power	41.5kW	56kW
Power to cavity	83kW	113kW
Cu losses/cav	20kW	28kW
Coupling (beta)	4.2	4.0
Cavity voltage	250kV	300kV
Cavity gap	4cm	5cm
Bucket height	4.5 %	4.5 %

Chosen!



Alt I: Represents a solution for a 60% ID equipped ring, with the present MAX II/ MAX III cavities.
Alt II: Represents a solution for a fully ID equipped ring, with slightly modified MAX II/MAX III cavities.

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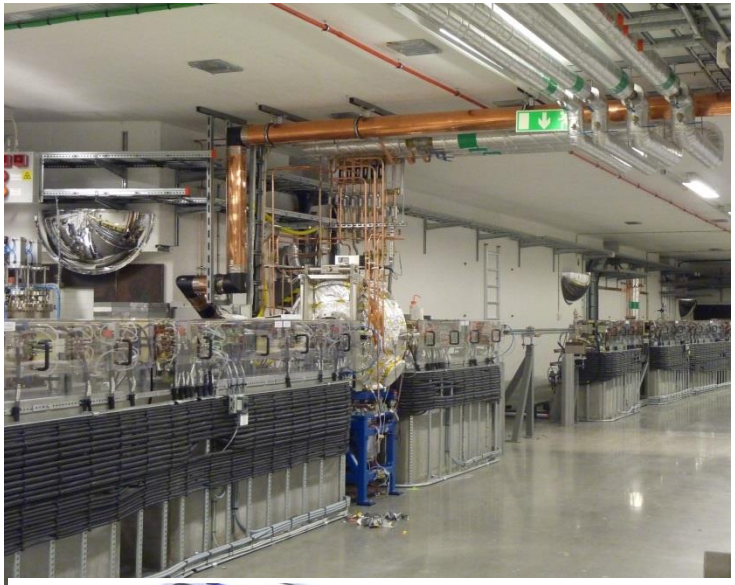
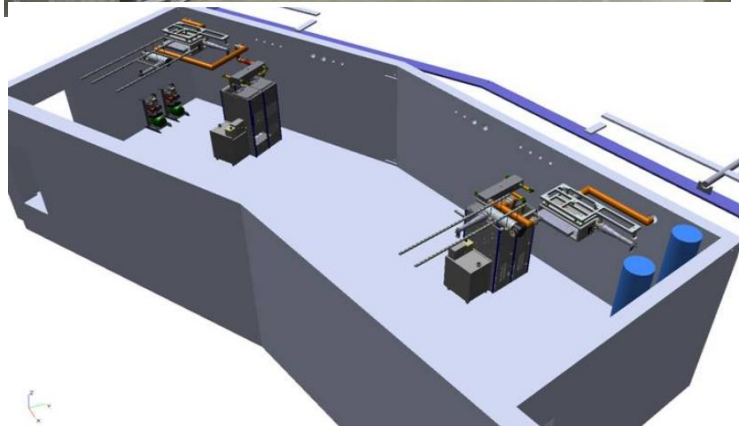
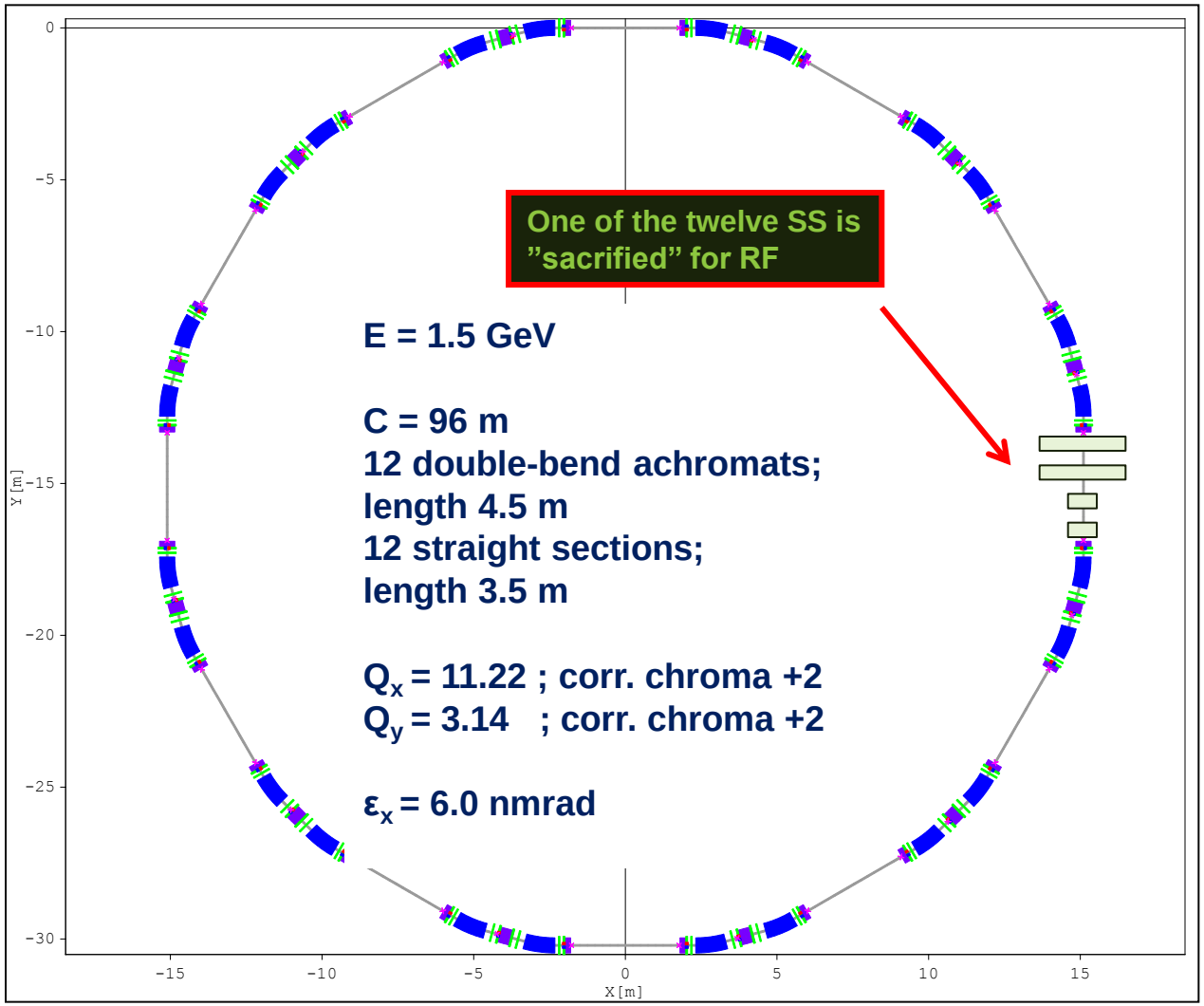
Ring RF System - 3 GeV Ring

- The main cavities are placed in the second short straight section of six consecutive achromats.
- Each RF-room contains two RF power plants.





MAX IV 1.5 GeV - Storage Ring



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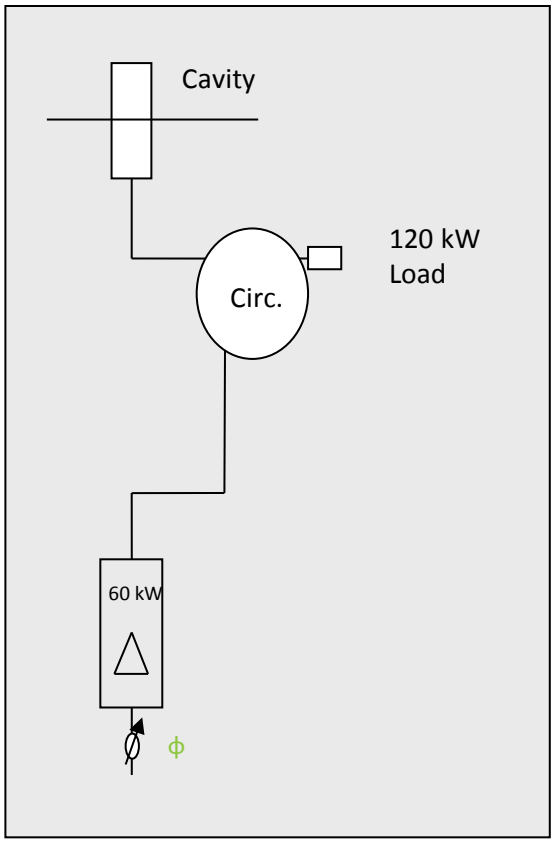
Ring RF System - 1.5 GeV ring

	Lund	Krakow
Case	I	II
Energy loss with Ids	130keV	150keV
Circulating current	0.5A	0.5A
Total beam power	65kW	75kW
Total RF voltage	0.56MV	0.5MV
Number of cavities	2	2
Cavity shunt impedance	3.2Mohm	3.2Mohm
Cu losses	49kW	39kW
Total RF power needed	114kW	114kW
Nr of RF stations	2	2
Nr of transmitters	2	2
Transmitter power	28.5kW	28.5kW
Power to cavity	57kW	57kW
Cu losses/cav	24.5kW	19.5kW
Coupling (beta)	2.3	2.9
Cavity voltage	280kV	250kV
Bucket height	4.0%	3.5%

Table 1: Two anticipated RF scenarios for the 1.5 GeV ring.



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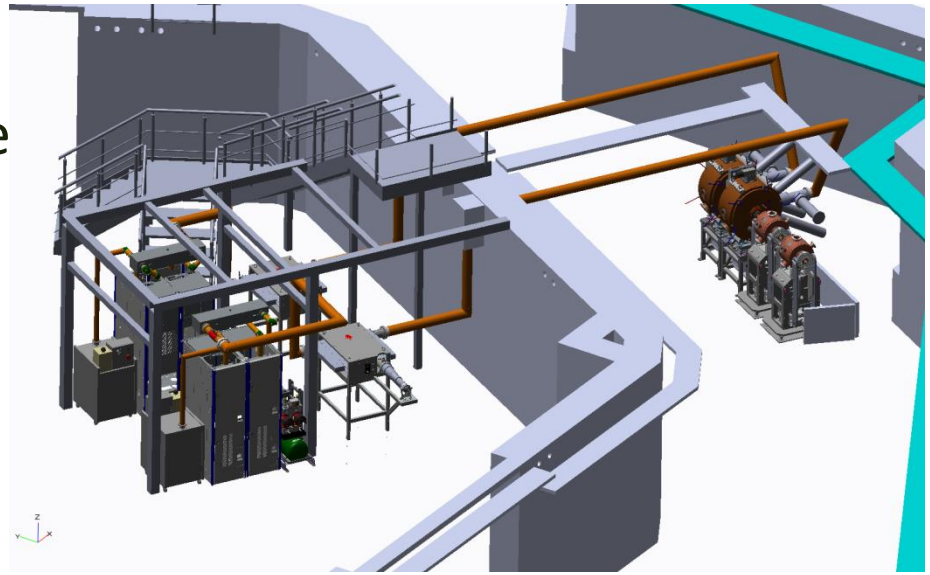
Ring RF System - 1.5 GeV Ring

- Two Main Cavities and two Harmonic Cavities occupy one straight section
- Two 60 kW Power Plants are placed inside the ring.



Ring RF System - Cavities

- Cavities (100 and 300 MHz)
- All main cavities including two for Solaris was Delivered October - December 2013
- Ten main and five HC has been conditioned at old Max-lab.

Main Cavities - Conditioning

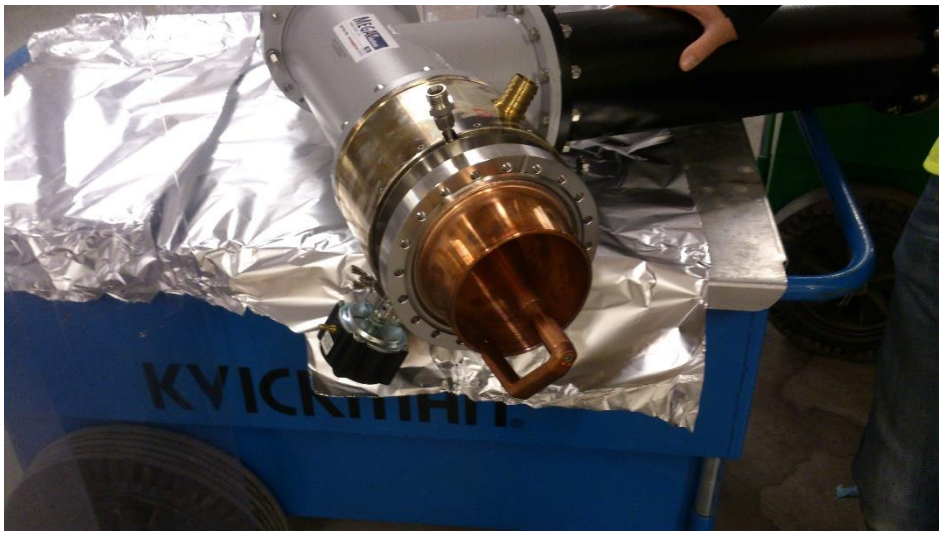
- The cavities were delivered baked (3 days, 120 degree), with power coupler attached (β = 1).
- A 600 l/s ion pump is attached. All cavities in the low 10^{-10} mbar range.

- So far, 9 main cavities (7 for MAX-IV, 2 for Solaris) have been conditioned to ~ 25 kW.
- Prototype: ~ 1 year (!)
- 2nd Cav # 11: ~ 3.5 months
- 3rd Cav # 08: ~ 3 months
- The following 5 cavities: ~ 5 * 1 month (now a computer code was used! Robert Lindvall)
- 9th cavity # 06: 2 weeks
- 10th cavity #09: was only conditioned to ~ 3 kW (lack of time)

- When all surrounding systems work OK, ~ 3 weeks of conditioning is sufficient.
- ~1 week up to 50 W (!). Pressure raises up to $5*10^{-6}$ mbar!
- ~1 week to pass multipacting regime 3-5 kW. Sometimes a need to attach a turbo!
- Finally ~1 week to reach 25 kW stable operation, without more than 1 ”glitch” per day.
- ”Glitch” = Sudden high reflected power, however self extinguishing after ~ 60 µs.

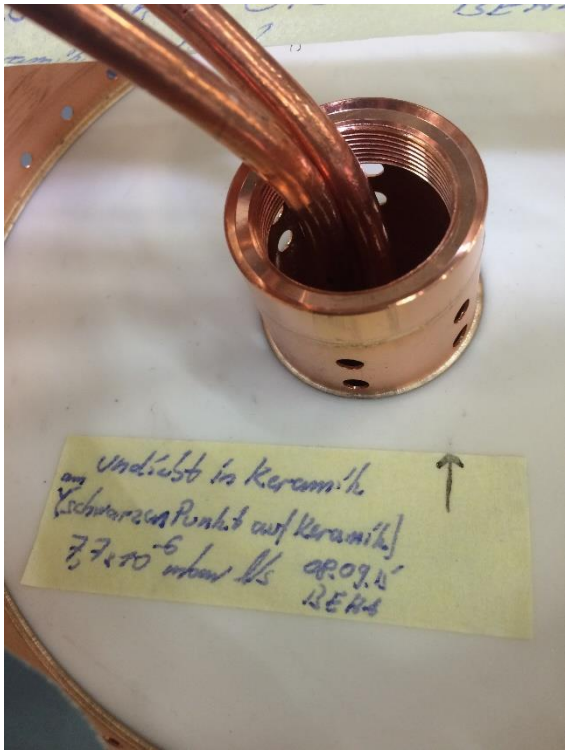
Main Cavities - Conditioning

- Multipacting problem origin: Coupler or Cavity body?



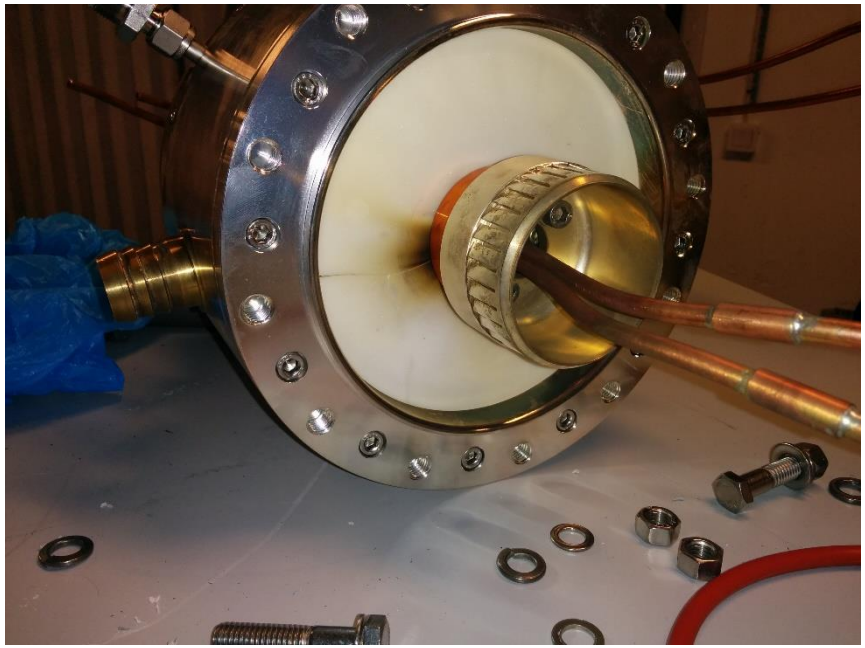
Main Cavities - Conditioning

A tiny defect in the ceramic window caused a leak ➔ p ~1*10^{-8} mbar



Main Cavities - Conditioning

- One more power coupler broken



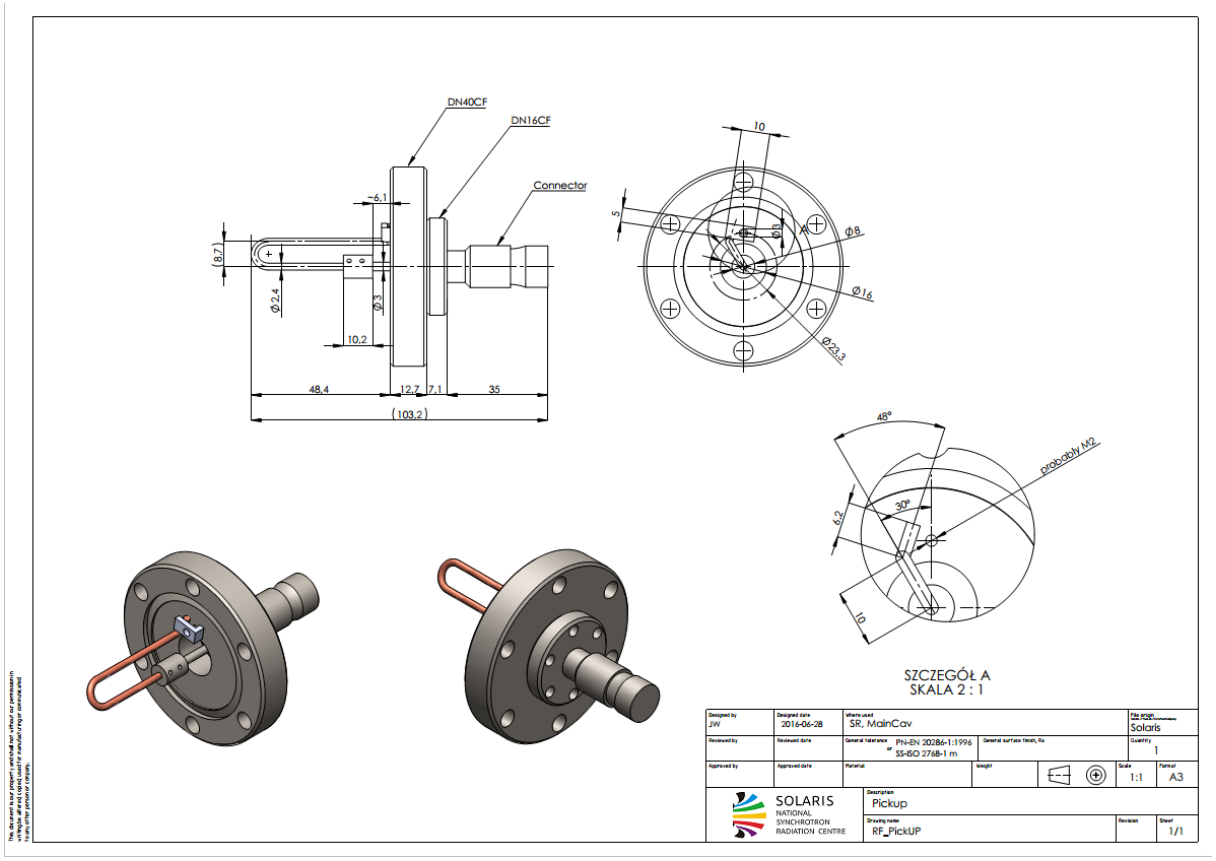
Main Cavities - Conditioning

- Six probe loop ceramics (out of 16) have started leaking.
- Only those we forgot to 50 Ω terminate! Heating problem?

The last half year, more leaks have appeared, even though terminated properly!!!

Main Cavities - Conditioning

- New pick-up without ceramic was manufactured by Max IV
- 10 replaced



Main Cavities - Conditioning

After conditioning we vented and turned coupler to β = 2.
We then measured f_r and Q_0 carefully:

Achromat #	16	17	18	19	20	1	
Resonant freq. N2-Vented & Force free [MHz]	100,112	100,019	99,93	100,13	99,973	100,042	
Difference compared to FAT [MHz]	-0,084	-0,001	0,014	-0,043		0,038	
Unloaded Q	20500	20400	20400	20250	20450	19700	Theory cyl-symm: 20923
Degradation due to Ports & Surfaces [%]	2,1	2,5	2,5	3,2	2,3	5,8	
Shunt Impedance (linac def.) [MΩ]	3,45	3,43	3,43	3,41	3,44	3,32	Theory cyl-symm: 3,52 MΩ
Required power to reach 300 kV [kW]	26,1	26,2	26,2	26,4	26,2	27,1	

Harmonic Cavities - Conditioning

- The 7 cavities (5 MAX-IV, 2 Solaris) were delivered non-baked, only leak tested.
- We performed ourselves the bake-out, with an Århus-coupler at β = 1 attached.
- Each cavity has two 100 l/s ion pumps. All cavities in the low 10^{-10} mbar range.

- All cavities have been conditioned to ~ 4 kW.
- ~ 5 *2 weeks per cavity (manual conditioning from a 300 MHz transmitter)

- ~1 week up to 50 W. Pressure raises up to $5*10^{-7}$ mbar!
- ~1 week to pass multipacting regime 0.5-2 kW.
- 4 kW without problems, and without ”glitches”.
- ”Glitch” = Sudden high reflected power, however self extinguishing.

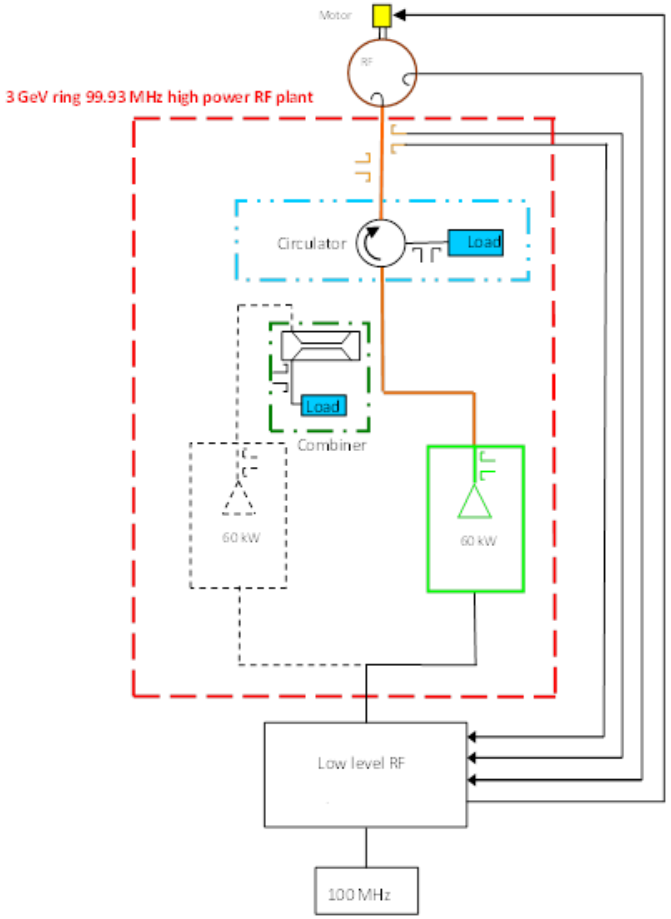
Harmonic Cavities - Conditioning

After bake-out, conditioning, removal of coupler, and installation we measured f_r and Q_0. A Δf_r = -140 kHz is expected.

Achromat #	13	14	15				
Resonant freq. @ FAT [MHz]	299,89	299,749	299,575				
Resonant freq. Pumped & Force free [MHz]	299,766	299,561	299,44				
Unloaded Q	20800	20800	21000				Theory cyl-symm: 21656
Degradation due to Ports & Surfaces [%]	3,95	3,95	3,03				
Shunt Impedance (linac def.) [MΩ]	5,32	5,32	5,37				Theory cyl-symm: 5,54 MΩ

Ring RF System – High Power Plants

- 120 kW RF power needed when fully equipped with ID´s
- Currently 60 kW
- Another 60 kW SSPA are added when needed
- Combiner already installed but not connected
- Singel high power (120 kW) circulator from AFT at the output
- 6 1/8” rigidline transmission lines from Exir Broadcasting, Sweden, who also was contracted for integration and installation



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Ring RF System – High Power Plants

- Contracts signed for
  - High power amplifiers (Electrosys, Italy). The delivery time was delayed because of severe financial problems in the company. The risk was too large to continue so the contract was canceled (June 2014). A new contract has been signed (September 2014)for delivery of 60 kW liquid cooled solid state power amplifiers (Rohde & Schwarz, Germany)
  - Circulators (AFT, Germany)
  - Transmission Lines and Integration Work (Exir Boadcasting AB, Sweden)
- Delivery of high power amplifiers: Two in December 2014 (January 2015) for test of circulators, two in February 2015 , two in March and finally two in June 2015 (1.5 GeV).

Ring RF System – High Power Plants

- Rohde & Schwarz 60 kW CW solid state liquid cooled amplifiers based on two 30 kW transmitters/amplifiers with additional power combiner
- >64% overall power efficiency
- High MTBF
- Compact: 2000 mm × 600 mm × 1100 mm (HxWxD)
- Coolant: glycol/water

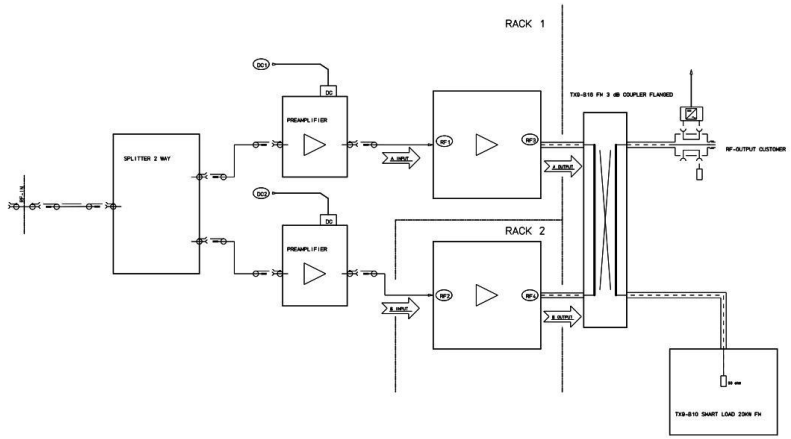
One pump unit and heat exchanger per rack

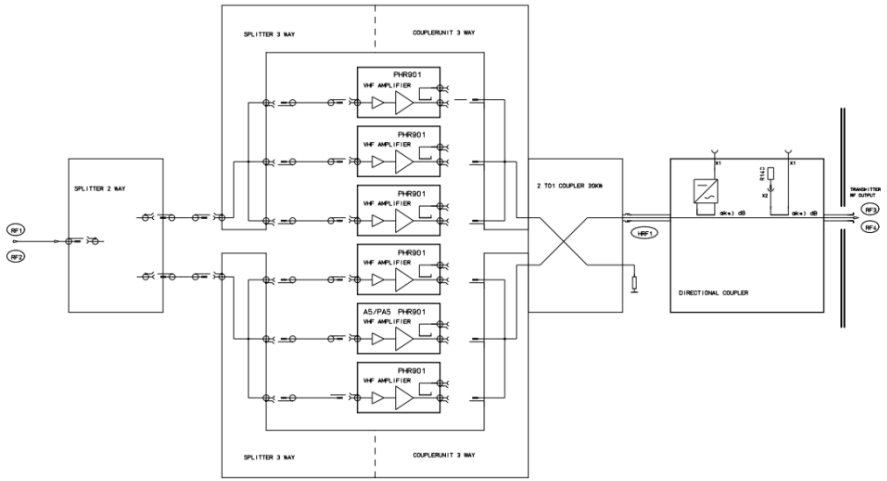
Ring RF System – High Power Plants

- 12 PA units in two racks
- 5 kW per PA
- Redundant Liquid cooling system
- Freq. range from 87.5 MHz to 108 MHz

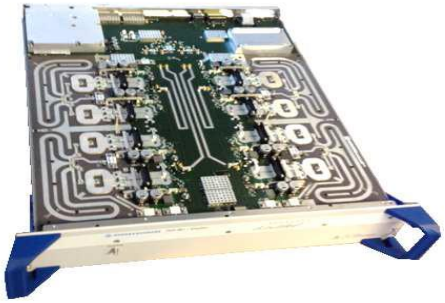
- Few changes from off-the-shelf product means lower price
- Modified from constant output power to constant gain

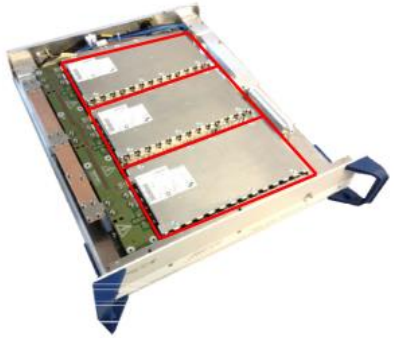
- Efficiency values where measured in the FAT:
  - Overall efficiency at full power 60,2 %
  - Overall efficiency at -3 dB power level 45,3 %
- With new software with possibility to change the DC voltage of the amplifiers:
  - Overall efficiency at full power 66,1 %
  - Overall efficiency at -3 dB power level 59,1 %



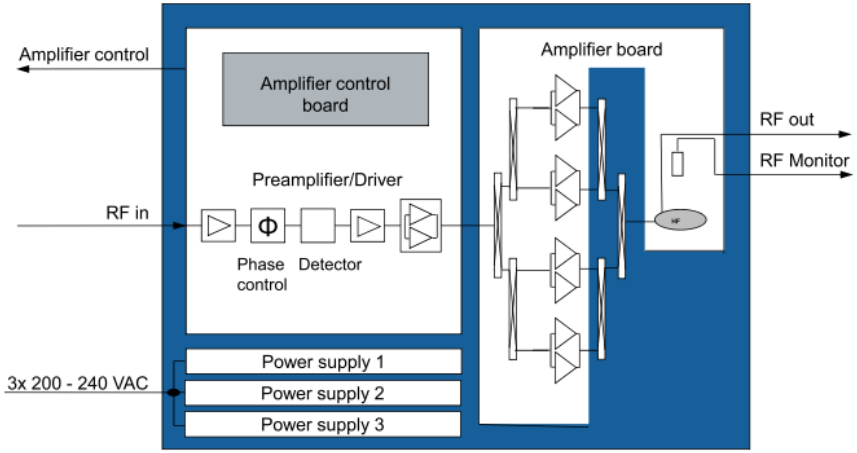


Ring RF System-PA moduls





- Nominal power 5.0 kW Constant Gain mode
- Controlled via CAN bus
- Integrated harmonics filter
- Voltage 3 x 230 V AC ± 15% / 47 .. 63 Hz
- Transistor 50V LDMOS Freescale MRFE6VP61K25H
- 8 Finale Stage transistors
- 3 single-phase power supply units
- 90% of nominal output power with 2 PS
- Harmonic attenuation up to 1 GHz at Pnom > 85 dB



High Power RF Systems Installation

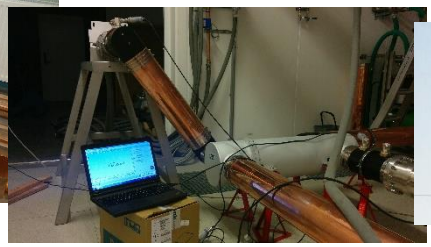
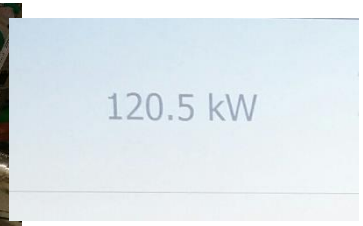
- High Power Amplifiers
- 120kW Circulators
- 120 kW 3dB Couplers
- 6 1/8” EIA Coaxial Lines





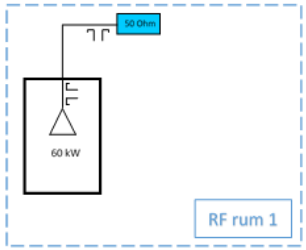


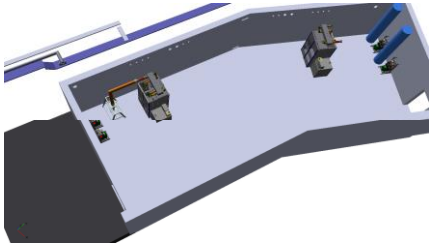


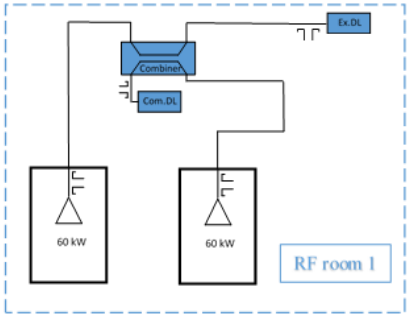

Ring RF Systems – SAT of the High Power Plants and Circulators

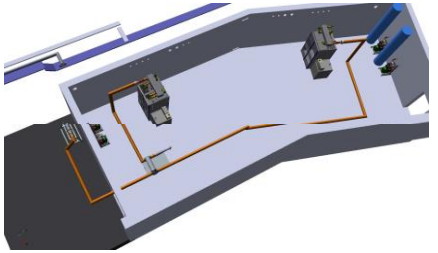
- One High Power Amplifier
  60 kW to load



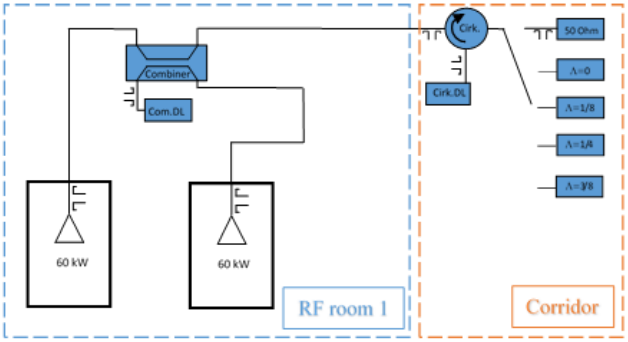


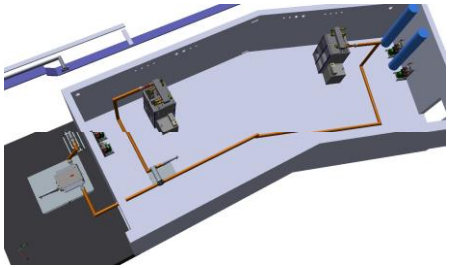
- Two combined HPAs
  120 kW to load





- 120 kW circulator Port 2 connected to :
  -50 Ohm water load
  -EIA 6 1/8”-Short via coax waveguide length 0, 1/8, ¼, 3/8 …lambda





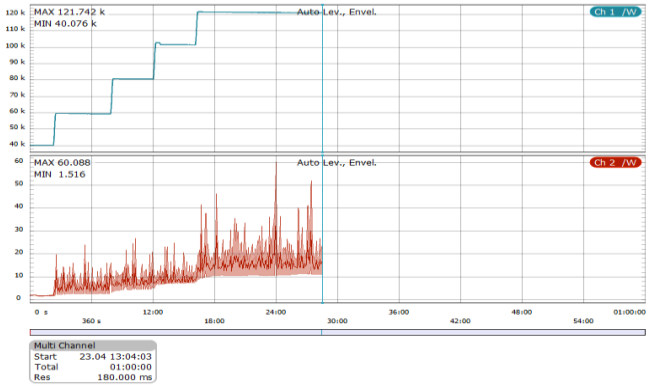
Ring RF System – SAT of Circulators

- FAT/SAT and retuning of TCU was performed on 8 units

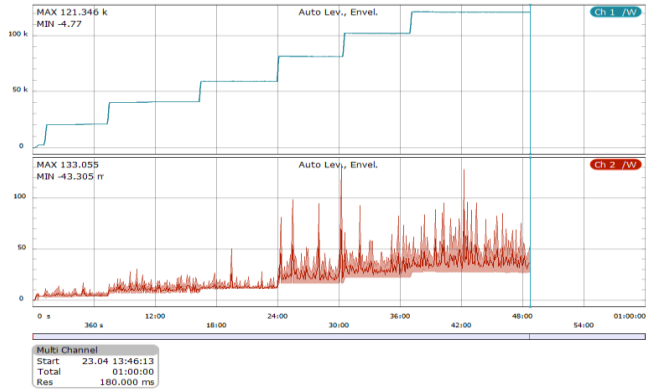
- Two test conditions with regards to the termination at port 2:
  (1) matched water load and
  (2) short circuit of variable phase .

Fast RF feedback control

Port 2 Mached Load



Port 2 Short Λ=0



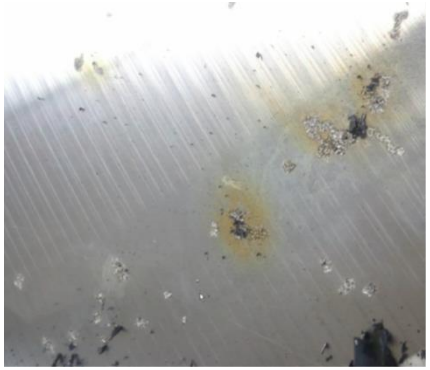
Ring RF System – SAT of Circulators

- Fifth circulator in row for test expired arc att 100kW in configuration to matched load.
- Circulator returned to AFT
- Damage is visible at ferrite close to port 1. Bottom side of cooling disc with ferrites shows massive arcing damages. Bottom side of circulator housing shows arc traces on the aluminum surface. Probably very small ferrites chips or local contamination caused arcing at lower power levels already.

Ferrites are damaged severely.

- 1: Remove damaged ferrites, clean cooling disc, replace ferrites by new ones.
  2: Clean surface of inner housing. Rework surface of inner housing.
  3: Reassembly of Circulator, all mech. & physical testing
  4: Electrical retuning of Circulator, TCU calibration

Ferrite chips and burning marks close to port 1.

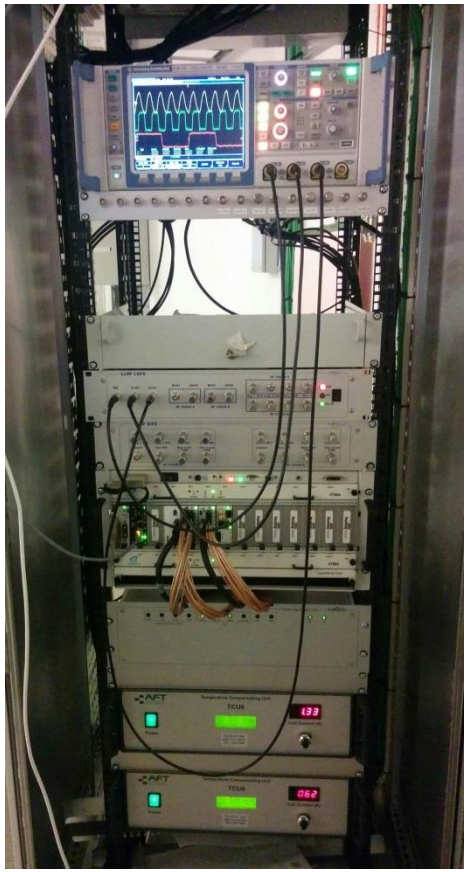


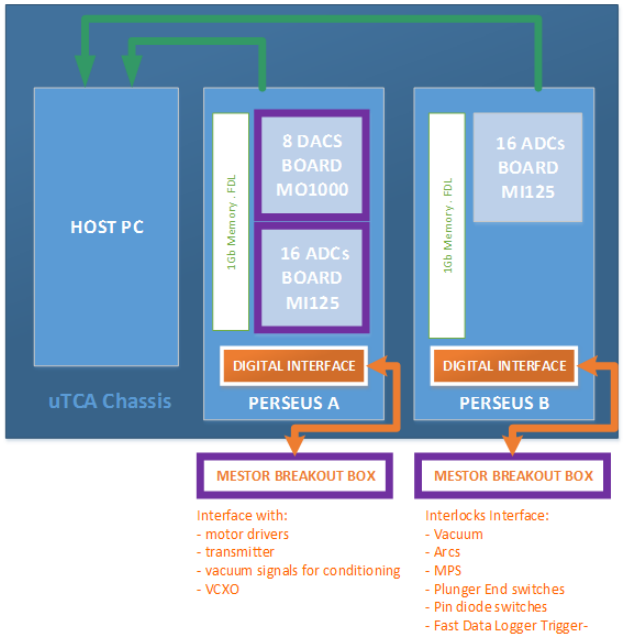
Aluminum surface of the house is damaged by arcs.

Digital Low Level RF

Design by Angela Solom
GUI by Antonio Milan

- The DLLRF is based on the Perseus FPGA platform from Nutaq. 3 units is in operation in the 3 GeV ring controlling two cavities each.
- It is possible to implement two independent loops besides the tuning loop. One controlling the amplitude of the cavity field and one the phase of the forward power. Either I / Q or polar loops can be selected.
- It has a fast data logger for post-mortem analysis.
- TANGO

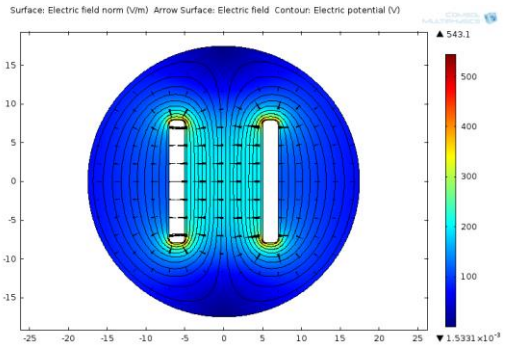




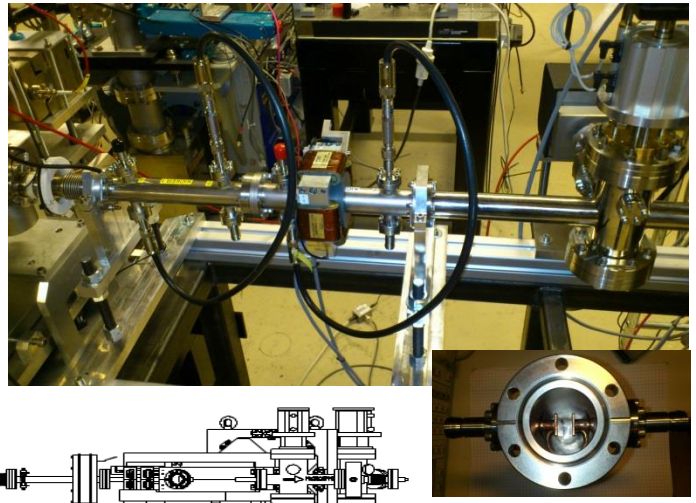
Chopper for Ring Injection

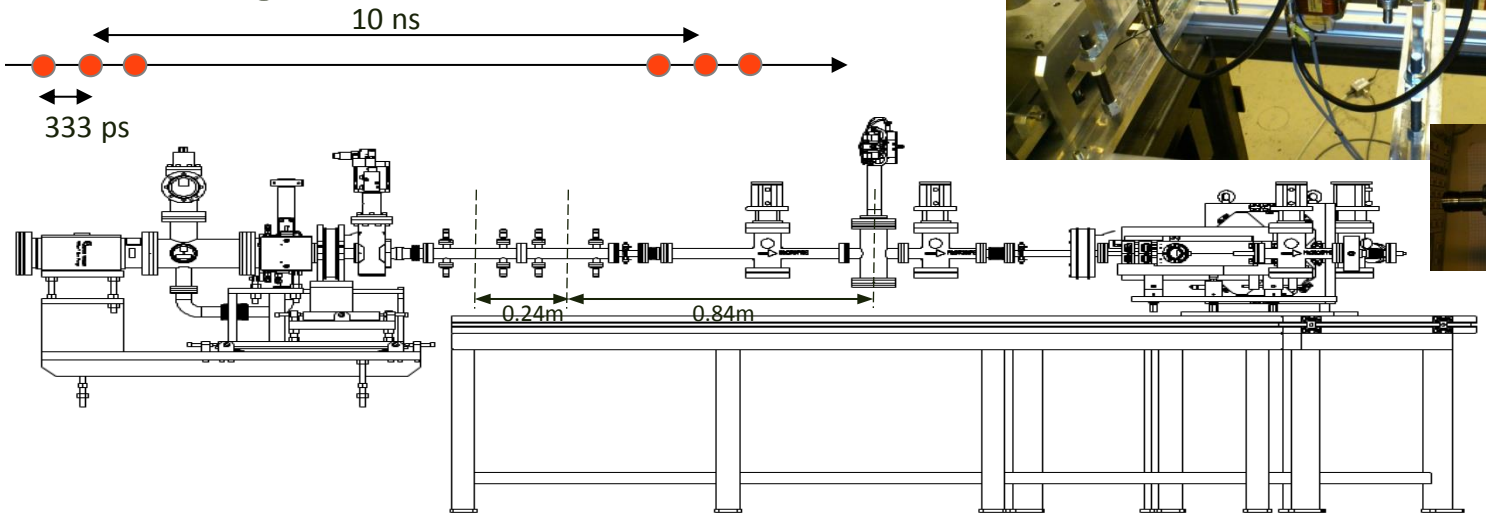
- Has two identical vertical kickers.
- The kickers consist of a 15 cm long stripline pair with a characteristic impedance of 50 Ω for odd TEM modes.
- Both electrodes are fed by RF
- An aperture is located downstream. The unwanted bunches will be dumped here.
- The aperture can be selected so the wanted bunches either passes a 1 mm iris, a 2 mm iris, or over an edge.

2 D design

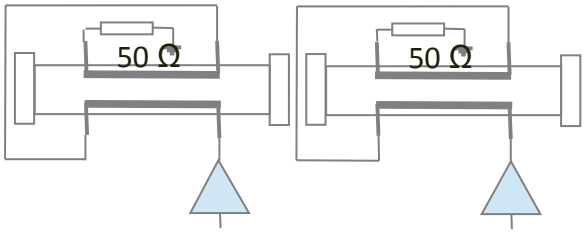


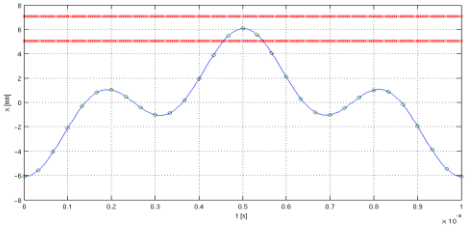
If $\phi_1=-\phi_2 \rightarrow$ Zo=49.9Ω
If $\phi_1= 0 \rightarrow$ Zo=63.8Ω
If $\phi_1= \phi_2 \rightarrow$ Zo=88.2Ω

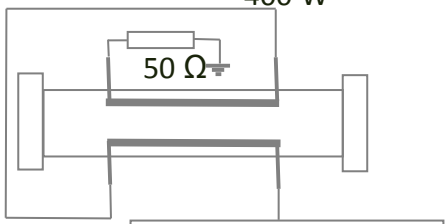


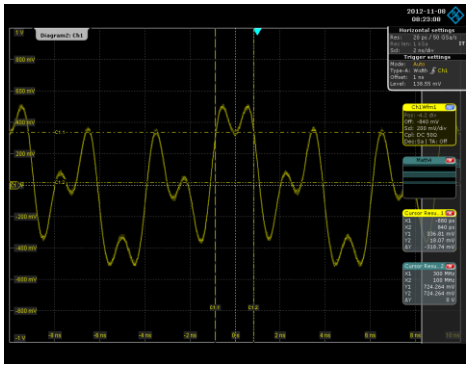


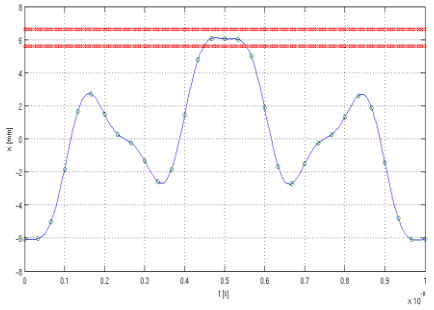
Chopper system for ring injection





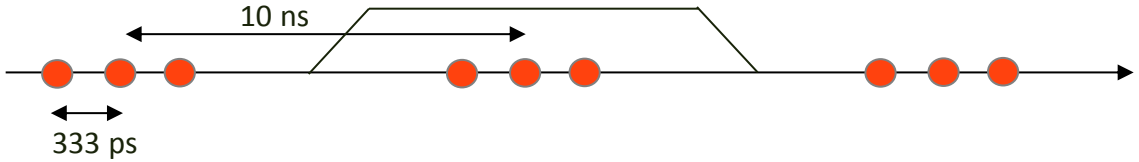






Crosstalk <-31db

100 MHz ~400 W 300 MHz ~1 kW 700 MHz ~300 W



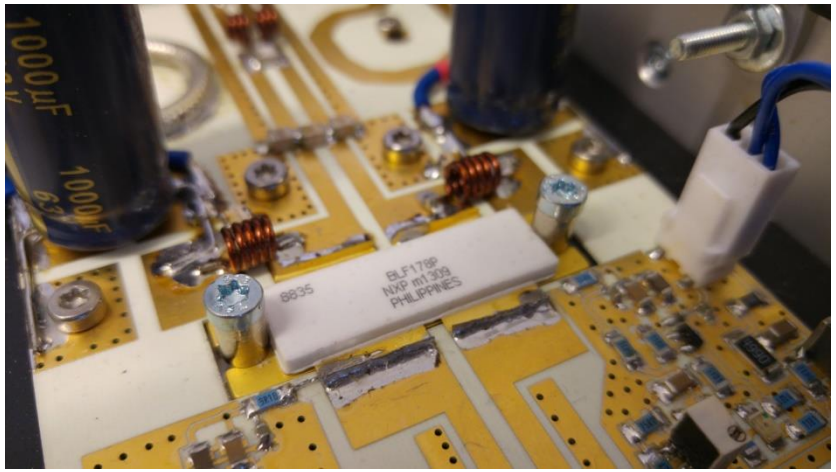
Chopper system for ring injection Amplifiers

- Power requirement
  - 100 MHz ~ 400 W
  - 300 MHz ~ 1000 W
  - 700 MHz ~ 300 W
- In-house design
  - Air cooled
  - Pulsed
- 2 stage, 20dB gain/stg.
- Mini-Circuit predriver 20dB gain
- Controller PIC processor

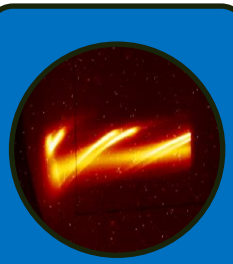
	Req. Pw.	Achieved Pw. Pulse	Achieved Pw. CW	Device	Gain
100 MHz	400W	1200W	200W	BLF178	~ 60dB
300 MHz	1000W	1000W	200W	BLF578	~ 60dB
700 MHz	300W	550W	200W	BLF888	~ 60dB

Chopper system for ring injection Amplifiers

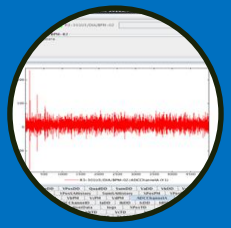
Design and development of pulsed solid state power amplifiers for 100, 300 and 700 MHz solid state power amplifiers



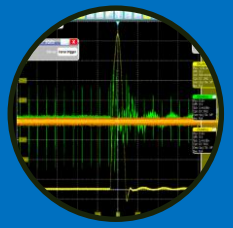
3 GeV Ring Commissioning Timeline



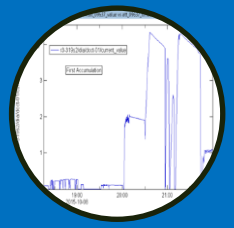
Beam in TR3
Aug 11
2015



First Turn
Aug 25
2015



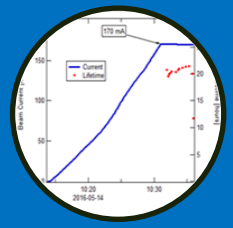
Stored Beam
0.1 mA
Sep 15
2015



Stacking
4 mA
Oct 08
2015

First Light
Nov 2
2015

Feb&March
2016
First IVUs

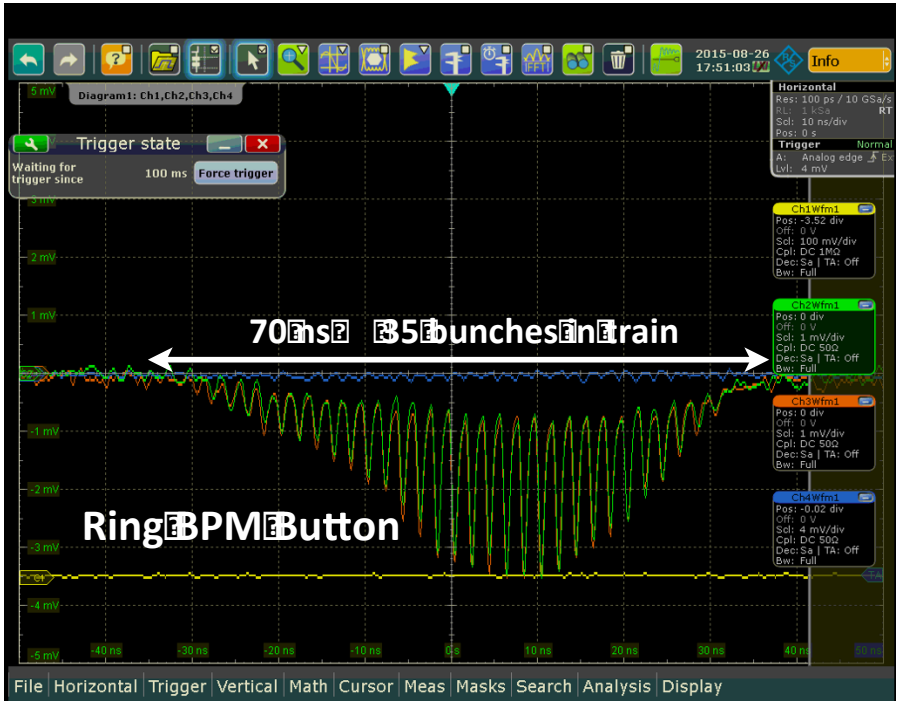


198 mA
July 9, 2016

MAX IV LABORATORY

3 GeV Storage Ring Commissioning

- First beam into full 3 GeV transfer line (TL) on Aug 11
- TL optics fixed, successful injection into 3 GeV SR on Aug 19



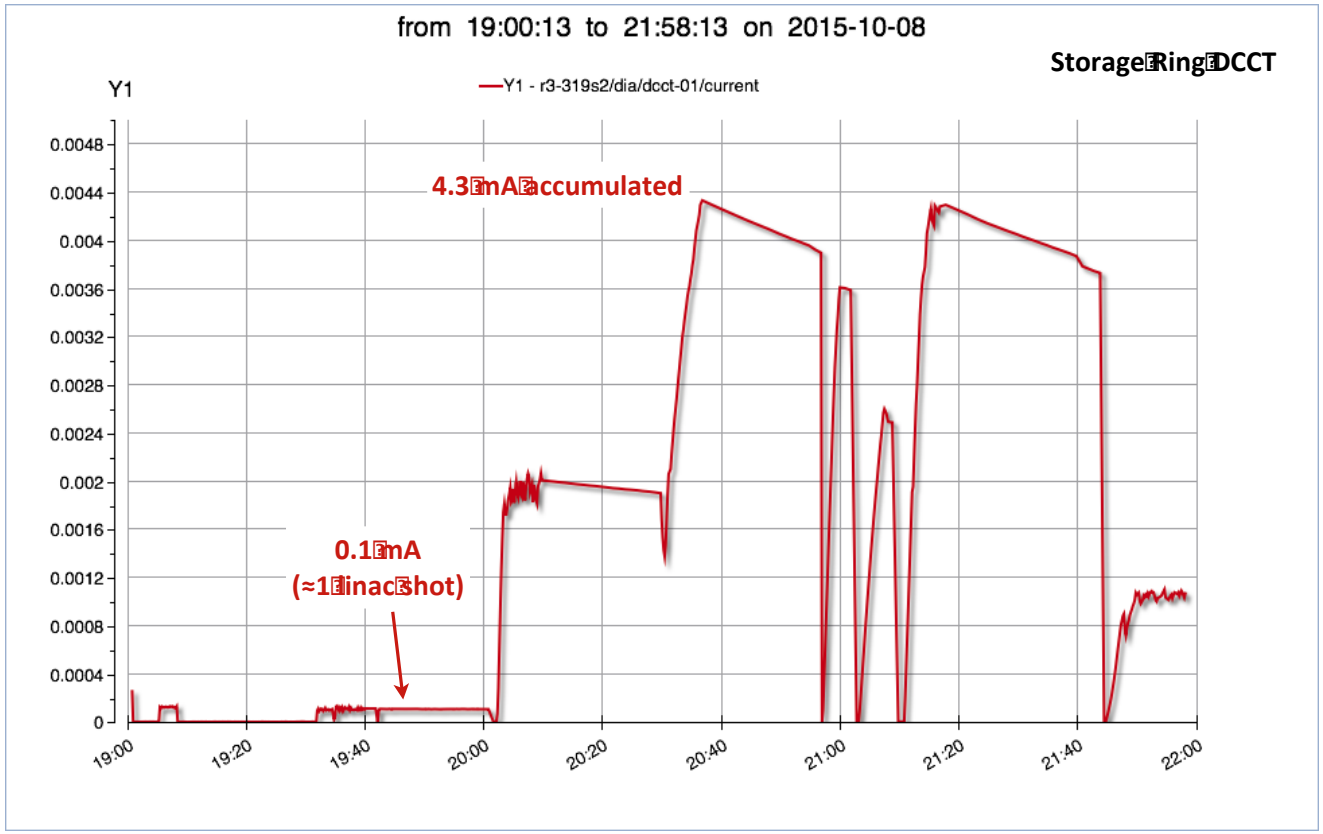
MAX IV LABORATORY

3 GeV Storage Ring Commissioning

- 2015 Aug 25, 10pm: reached first full turn without exciting a single corrector & all magnets at nominal optics for 3.0 GeV
- Without sextupoles & octupoles lost beam in straight 11
- After a few minutes of manual corrector adjustments and optics tweaking (mainly in TL and end of linac) recorded 3 passages
- After RF conditioning (3 cavities ready for beam @ 15-20 kW) and various other fixes...
- First stored beam on Sep 15 ➔ ≈0.1 mA (≈170 pC from linac)

3 GeV Storage Ring Commissioning

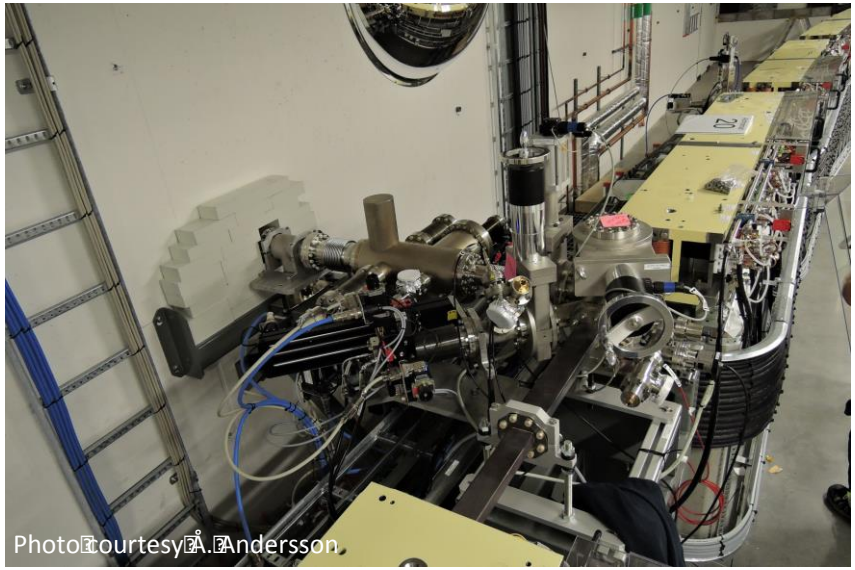
- First stacking observed Oct 8
- Phasing 2 ring cavities ➔ maximize f_s and improve inj. rate

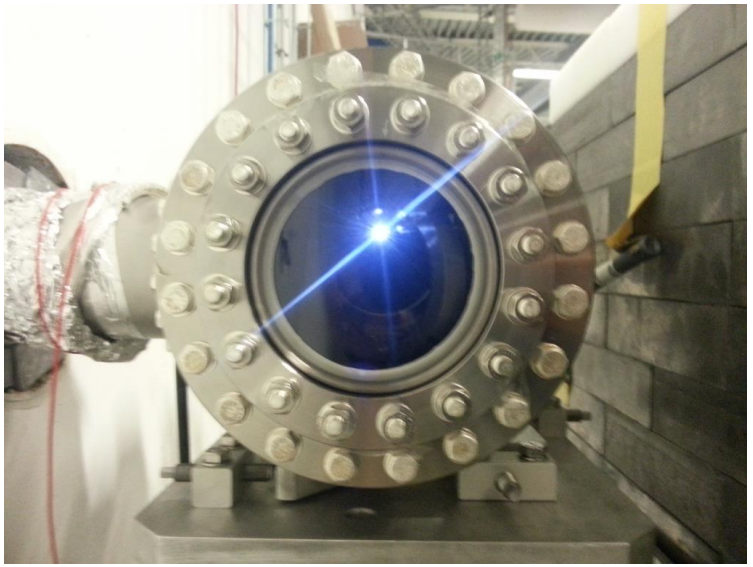


MAX IV LABORATORY

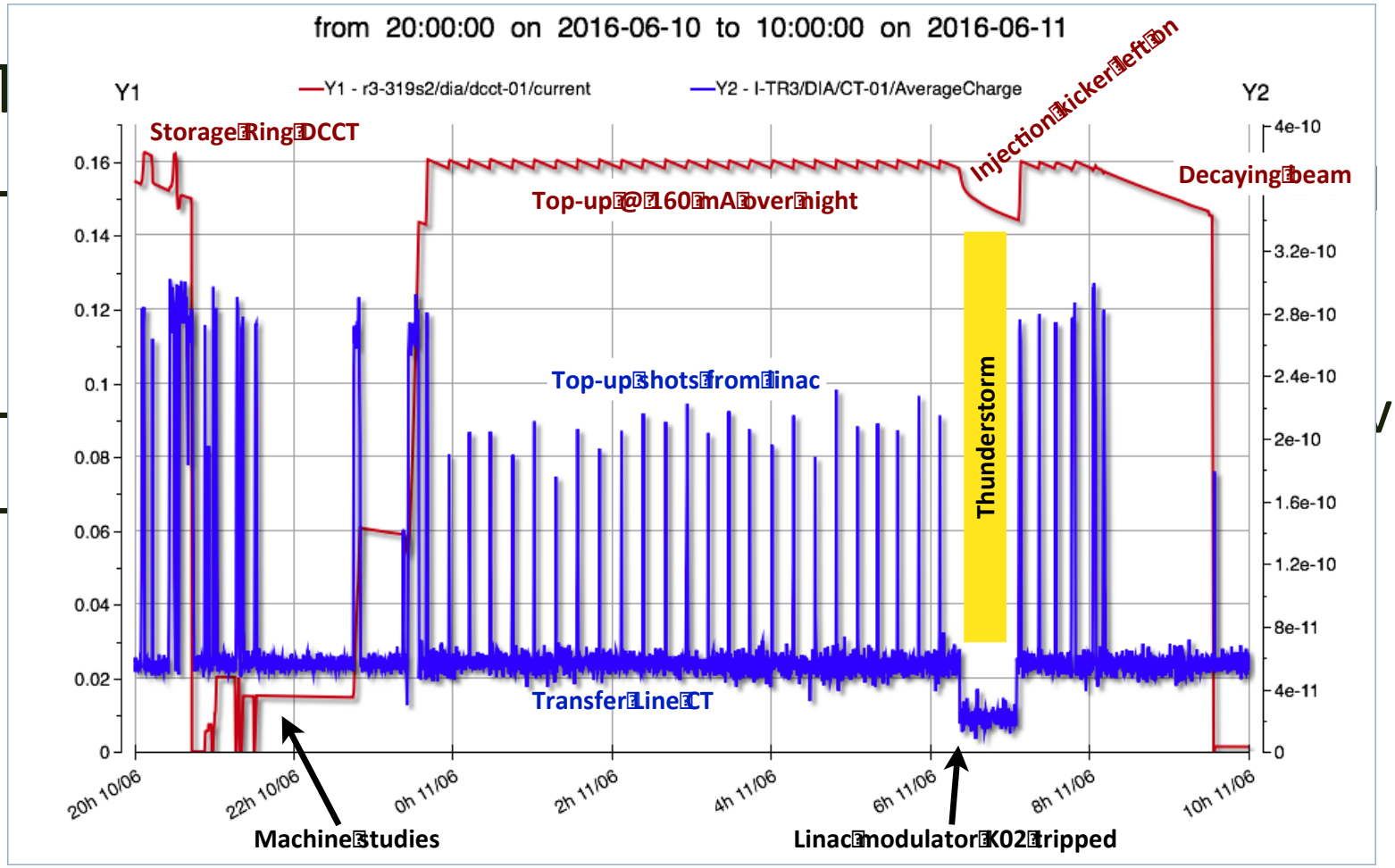
3 GeV Storage Ring Commissioning

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2 2015





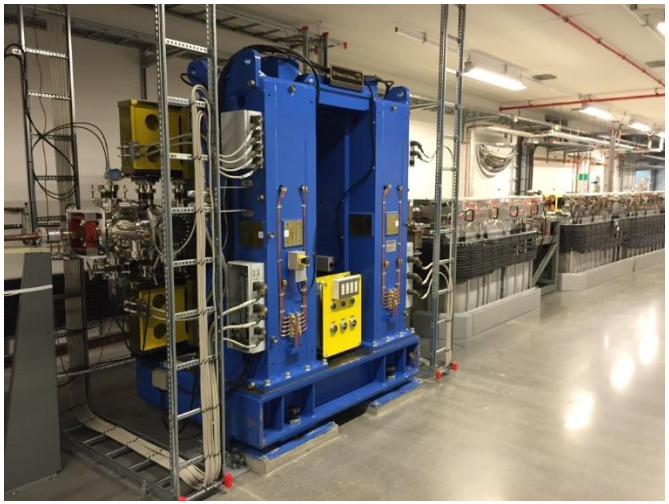
3 GeV Storage Ring Commissioning



MAX IV LABORATORY

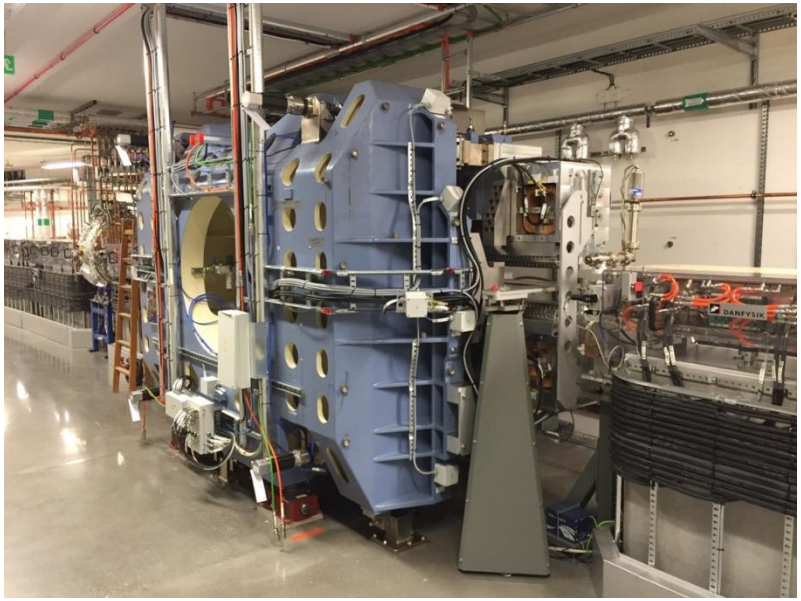
3 GeV Storage Ring Commissioning

- First two IVUs installed during Feb 2016 shutdown for BioMAX and NanoMAX beamlines
- ID & BL commissioning started Apr 2016
- May 11: 10 mm gaps on both BLs May 11-19: first monochromatic beams (on detector / 11 keV)
- June 8/9: First diffraction patterns
- June 20: First nano-focus @ NanoMAX
- 198 mA present stored current record



3 GeV Storage Ring Commissioning

- During recent summer shutdown installed three new Ids

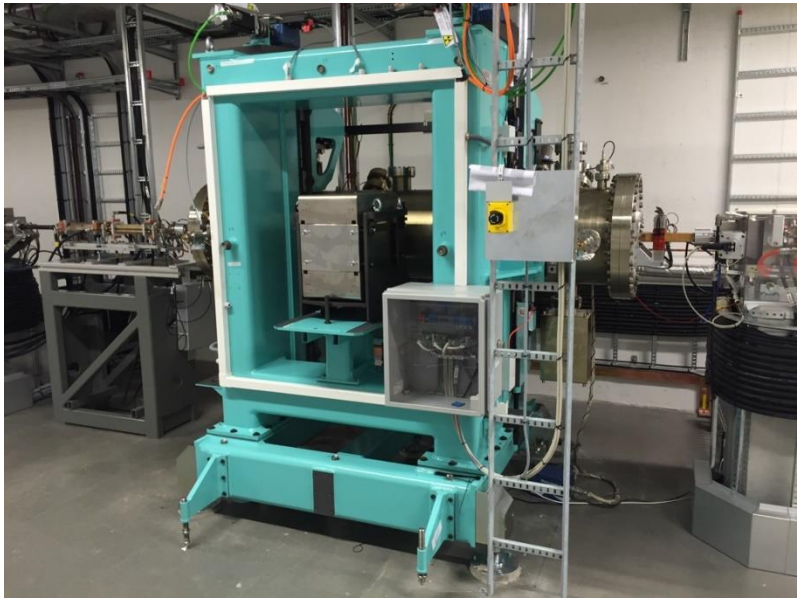


EPU48 → VERITAS BL (RIXS)

EPU53 → HIPPIE BL (AP-XPS, AP-XAS)

3.9 m magnetic length, 69/77 periods,
11 mm min. magnetic gap, ≈1.1 T peak field

Manufactured at MAX IV



In-vac Wiggler → BALDER BL (XAS, XES)

2.0 m magnetic length, 50 mm period,
4.2 mm min. magnetic gap, ≈2.4 T peak field

Manufactured by SOLEIL

Outlook

- Continue commissioning of 3 GeV storage ring
  - optics & IDs
  - diagnostic beamline
  - RF conditioning main cavities and LCs (high current)
  - BbB feedback commissioning
- Just started commissioning of 1.5 GeV storage ring
  - first IDs to be installed in 1.5 GeV SR during early 2017
- "Friendly users" arrive Nov 2016 & first open user call for Mar 2017
- What remains to be installed during 2017
  - 2nd diagnostic BL on 3 GeV SR
  - 2 additional linac stations
  - 3 IDs in 3 GeV SR (2 IVUs, 1 EPU) & 3 IDs in 1.5 GeV SR (1 new EPU, 1 EPU & 1 PU from MAX II)

MAX IV Inauguration

- Brightest time of the year: June 21, 2016 @ 13:08:55 (local noon)

While the rest of Sweden was celebrating Midsummer like this...

MAX IV Inauguration (cont.)

- Brightest time of the year: June 21, 2016 @ 13:08:55 (local noon)

...we inaugurated our new facility.

Thanks for your attention
Questions?