Radio Frequency System for Diamond II

C Christou

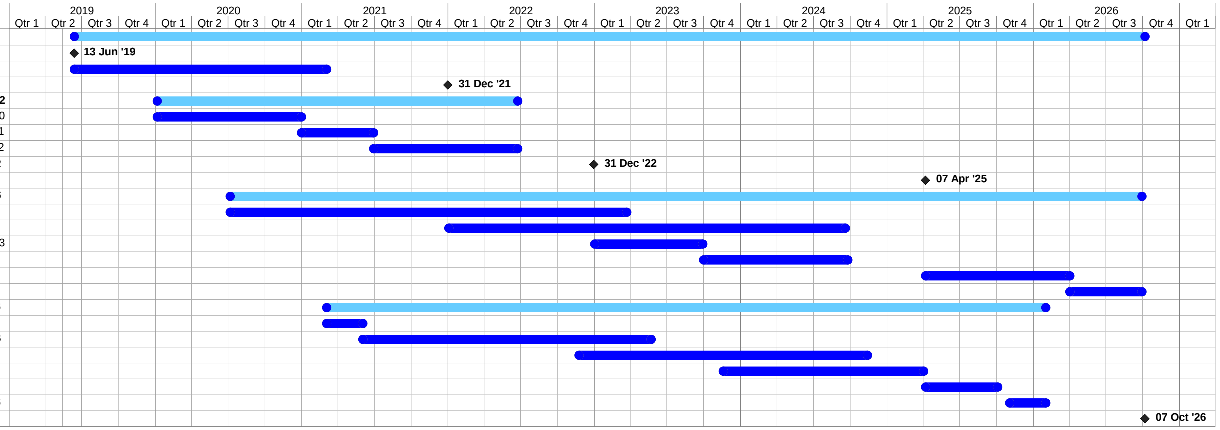
ESLS-RF
Diamond Light Source 24th/25th
October 2019

Project outline

- Covers period from approval of CDR to end of Dark Period
  - June 2019 to October 2026

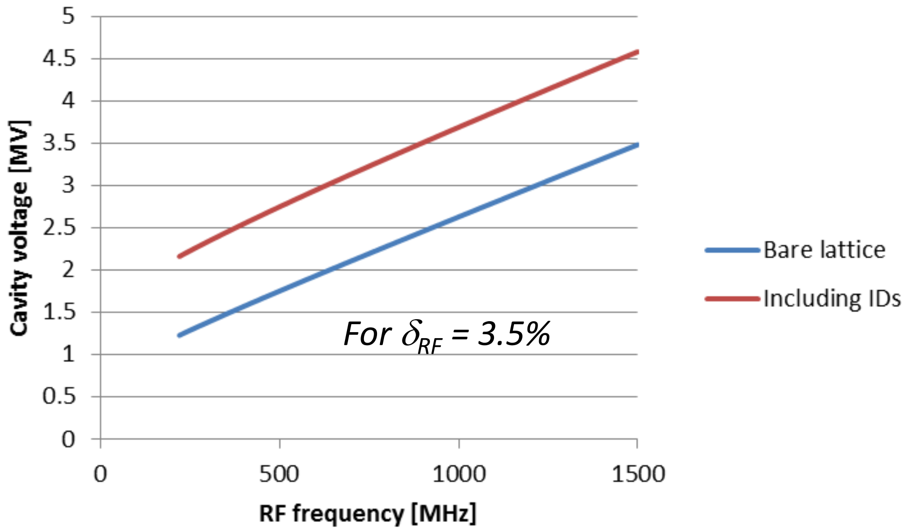
Courtesy S. E. Hughes

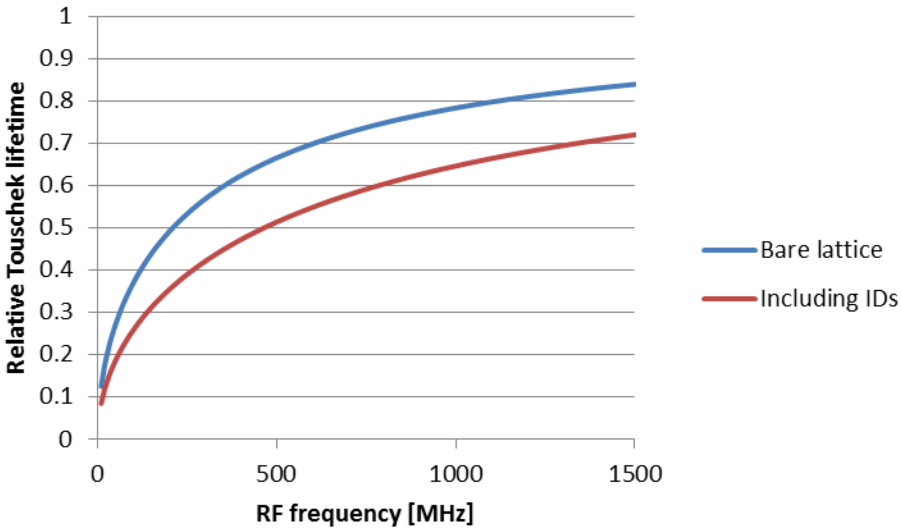
ID	Task Name	Duration	Start	Finish
0	**D-II Machine Outline Project Schedule**	**1888 d**	**13 Jun '19**	**07 Oct '26**
1	**CDR Approval - Milestone**	0 d	13 Jun '19	13 Jun '19
2	**REFERENCE DESIGN**	21 emons	13 Jun '19	04 Mar '21
3	**Project Approval - Milestone**	**0 d**	**31 Dec '21**	**31 Dec '21**
4	**DIAMOND-II ASSEMBLY BUILDING**	**632 d**	**06 Jan '20**	**24 Jun '22**
5	**DIAMOND-II ASSEMBLY BUILDING DESIGN**	12 emons	06 Jan '20	31 Dec '20
6	**DIAMOND-II ASSEMBLY BUILDING PROCURE**	6 emons	31 Dec '20	29 Jun '21
7	**DIAMOND-II ASSEMBLY BUILDING BUILD**	12 emons	29 Jun '21	24 Jun '22
8	**Diamond-II Building Complete - Milestone**	**0 d**	**31 Dec '22**	**31 Dec '22**
9	**Start of Dark Period - Milestone**	0 d	07 Apr '25	07 Apr '25
10	**STORAGE RING**	**1618 d**	**06 Jul '20**	**29 Sep '26**
11	**STORAGE RING DETAILED DESIGN**	33 emons	06 Jul '20	23 Mar '23
12	**STORAGE RING PROCUREMENT**	33 emons	03 Jan '22	19 Sep '24
13	**STORAGE RING PROTOTYPE COMPONENTS BUILD**	9 emons	02 Jan '23	29 Sep '23
14	**STORAGE RING GIRDERS BUILD**	12 emons	01 Oct '23	25 Sep '24
15	**STORAGE RING INSTALL**	12 emons	07 Apr '25	02 Apr '26
16	**STORAGE RING COMMISSIONING**	6 emons	02 Apr '26	29 Sep '26
17	**BOOSTER**	**1282 d**	**04 Mar '21**	**01 Feb '26**
18	**BOOSTER TENDER & SELECTION**	3 emons	04 Mar '21	02 Jun '21
19	**BOOSTER DESIGN & MANUFACTURE**	24 emons	02 Jun '21	23 May '23
20	**PARTIAL BOOSTER INSTALL**	24 emons	24 Nov '22	13 Nov '24
21	**PARTIAL BOOSTER SYSTEMS COMMISSIONING**	16.67 emons	19 Nov '23	02 Apr '25
22	**BOOSTER INSTALLATION COMPLETION & SYSTEMS COMMISSIONING**	6 emons	07 Apr '25	04 Oct '25
23	**BOOSTER COMMISSIONING**	**3 emons**	**03 Nov '25**	**01 Feb '26**
24	**User Beam Resumes - Milestone**	0 d	07 Oct '26	07 Oct '26



- Decisions to be made regarding the RF system for Diamond-II
  - Voltage and power — radiation loss and beam current
  - Operating frequency — technology and lattice driven
  - Cavity type — reliability, efficiency , cost and maintainability
  - Amplifier type — reliability, efficiency , cost and maintainability
  - Low level RF — reliability and flexibility
  - Higher harmonic cavity — effectiveness, ease of operation and cost

Fundamental RF parameters - Frequency





$$\delta_{RF} = \frac{U f_0}{\pi \alpha f_{RF} E} F$$

$$\tau_t \propto \sqrt{\frac{1}{1+\frac{C}{f_{RF}}}}$$

- Lower frequency minimises voltage requirement
- Higher frequency maximises Touschek lifetime
- 500MHz minimises voltage with limited lifetime compromise
  - Multiple cavity designs are available at this frequency
  - Several amplifier types can be used
  - Preserving Diamond frequency minimises disruption and cost

Precise operating frequency

- Lattice design gives f_{rf} = 499.460MHz with h = 934
  - How much of the Diamond RF can be used in Diamond-II?
  - Amplifiers have broad bandwidth but cavity tuning is more restrictive

Device	Minimum frequency	Maximum frequency	Notes
SR superconducting cavities	499.5 MHz	499.8 MHz	Upper limit may be possibly raised by further distortion, but risk of damage is high. Lower frequency may be extended by a smaller amount with further risk
SR normal conducting cavities	499.3 MHz	500.1 MHz	Minor further tuning is possible by changing water temperature
Booster cavities	499.5 MHz	500.0 MHz	
Linac structures	499.6 MHz (*6)	499.9 MHz (*6)	Tuning by water temperature only

- Superconducting cavities would operate on the edge of their range
  - Further tuning by deformation carries a risk of damage
- Normal conducting cavities are suitable for storage ring with no further work
- Present booster cavities and linac structures would need to operate at elevated temperature
  - Linac operating temperature would be 70°C
  - Test operation off frequency

Choice of Cavity – SC or NC

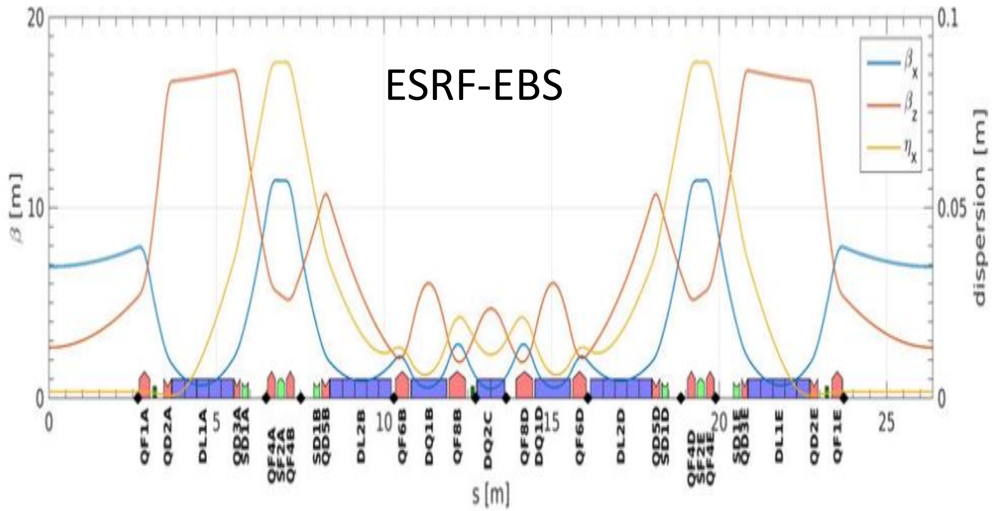
	Superconducting cavities	Normal conducting cavities
Wall power losses	Minimal	Significant
Infrastructure	Complex cryogenic plant Single point of failure	Water cooling
Field gradient	Higher	Lower
Fault tolerance	Any fault will bring down beam	Multiple low voltage cavities can introduce redundancy
Footprint	Large cryostat	Short flange-to-flange distance
Maintenance and repair	Difficult to repair Module must be warmed up Cryostat must be removed Surface treatment required	Simpler
Higher order modes	Less intense	More intense HOM-damped cavities available
Beam port	Large: long taper required	Small: shorter taper

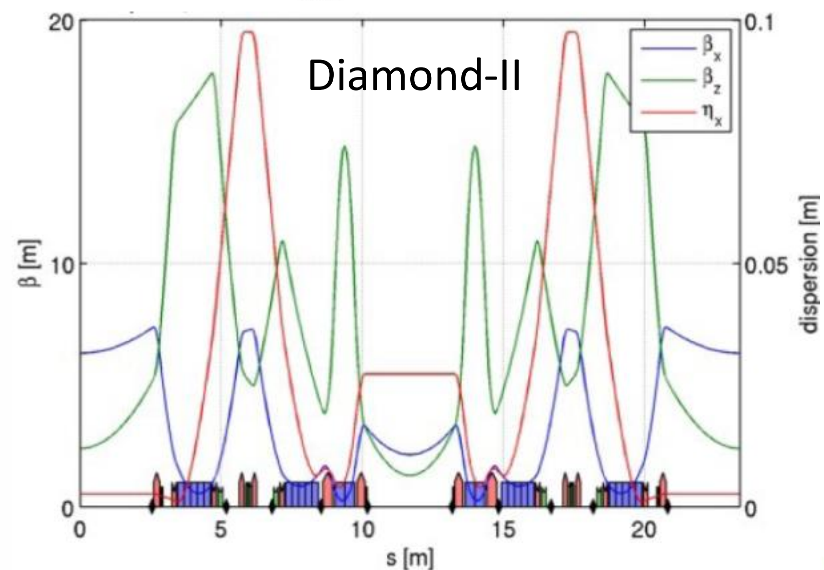
M-H6BA ("DTBA")

In the summer of 2015 it was decided to start looking into a 6BA, with mid-straights, and a collaboration was established with the AP Group of the ESRF.

Based on the ESRF-EBS H7BA, with the central DQ removed and opened up to create a mid-straight, the "**modified hybrid 6BA**" was developed and eventually became the baseline lattice, with an emittance of **130 pm at 3 GeV**, x20 less than Diamond.

Courtesy R. P. Walker

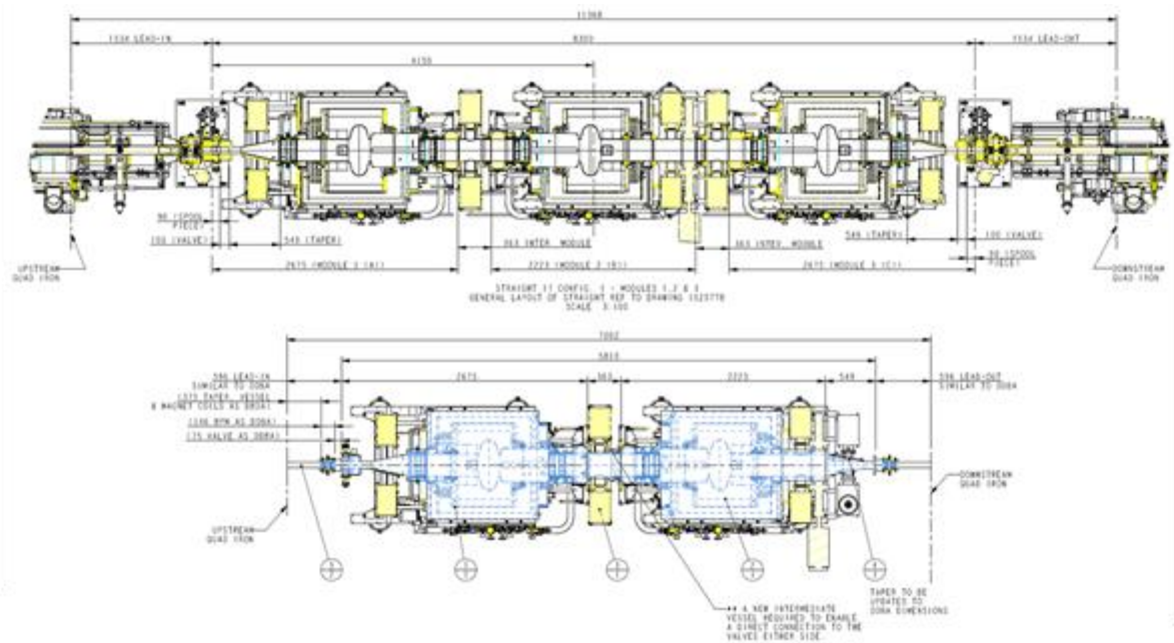




Superconducting cavity layout

- 2.7MV needed with all IDs
  - 3 superconducting cavities needed
  - Only space for 2 cavities in the RF straight

Reliable operating voltages	
Cavity A	1.1 MV
Cavity B	1.2 MV
Cavity C	1.4 MV
Cavity D	0.8 MV

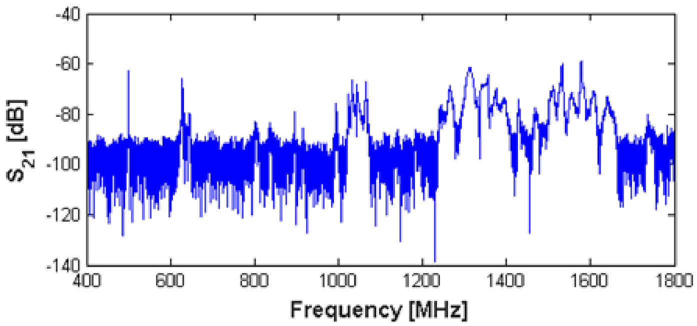


- 2.9m mid-section straight is too short for third superconducting cavity
  - Possible compromise on tapers or valves
  - Not recommended

EU HOM-damped cavity

- Superconducting cavities for Diamond are operating reliably at present
  - Past major failures have caused extended down-time
  - DLS has no facilities to repair failed SC cavities
  - SC cavities do not fit in lattice!
- Suitable normal-conducting cavity for Diamond-II
  - Simple and easily maintained
  - Voltage per cavity will be reduced
  - Power per amplifier will be reduced
  - Latest iteration of cavity installed at BESSY, Alba and ESRF (scaled for frequency)
    - Flanged joint at base of HOM damper waveguide removed to address trapped mode
    - Pickup coated at ESRF
  - Much smaller longitudinal footprint than SC cavity
  - Two cavities now installed in Diamond

Cavity	Coupling	Q_0	R_s
N16	5.17	33,000	3.75 MΩ
N18	5.25	33,000	3.75 MΩ

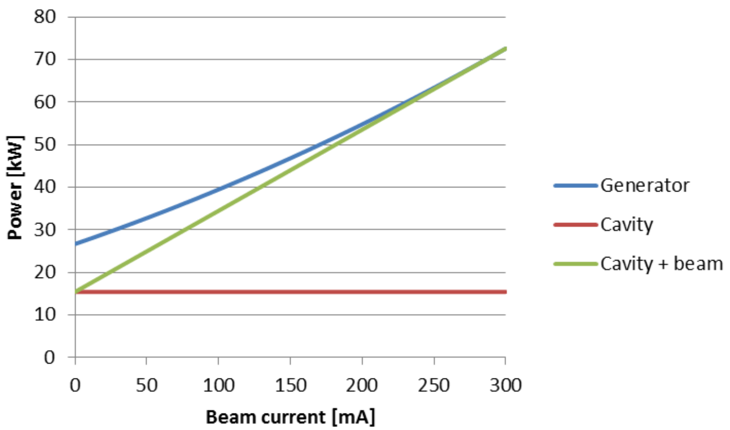


Operating parameters – NC Cavity

- 460kW required for 300mA beam with all IDs

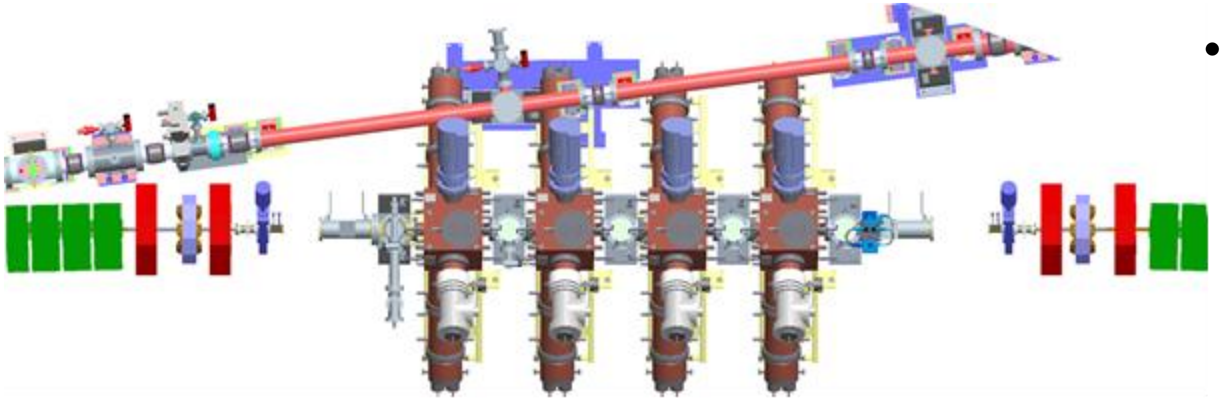
Number of cavities	6	7	8	9
Optimal cavity coupling	3.8	4.3	4.7	5.2
Individual cavity voltage	450 kV	386 kV	338 kV	300 kV
Generator power per cavity	104 kW	85 kW	73 kW	63 kW
Power dissipated per cavity	27 kW	20 kW	15 kW	12 kW
Power dissipated in all cavities	164 kW	140 kW	123 kW	109 kW

$$P_g = \frac{V_c^2}{R_L}\frac{\beta+1}{8\beta}\left[\left(1+\frac{2R_L I_b}{V_c}\cos(\phi)\right)^2+\left(\tan(\psi)+\frac{2R_L I_b}{V_c}\sin(\phi)\right)^2\right]$$

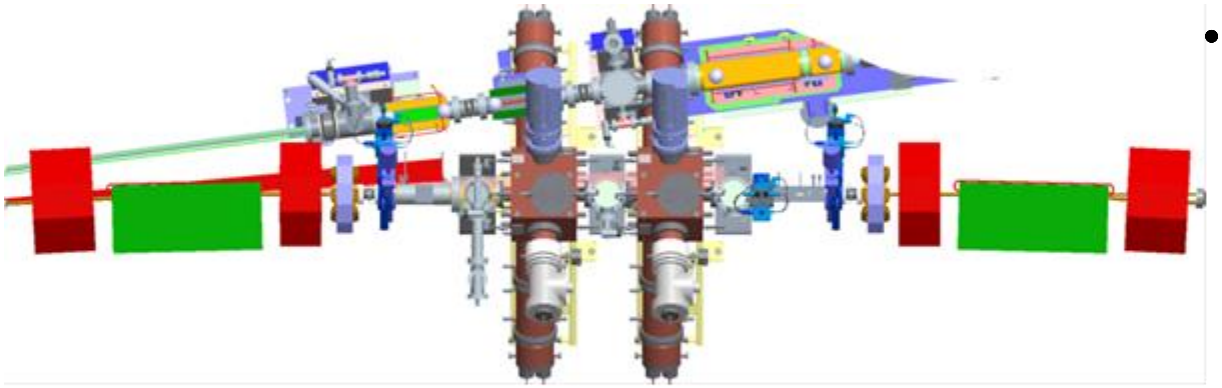


- Operation with 8 normal conducting cavities
  - Reduces voltage per cavity to conservative level
  - Gives acceptable total wall power losses
  - Allows redundant operation should one cavity fail
  - Enables cavities to fit in storage ring

Normal conducting cavity layout



- 4 cavities in RF straight
  - Pumps between cavities
  - Tapers and valves at end of assembly
  - Front-end threads between cavity limbs

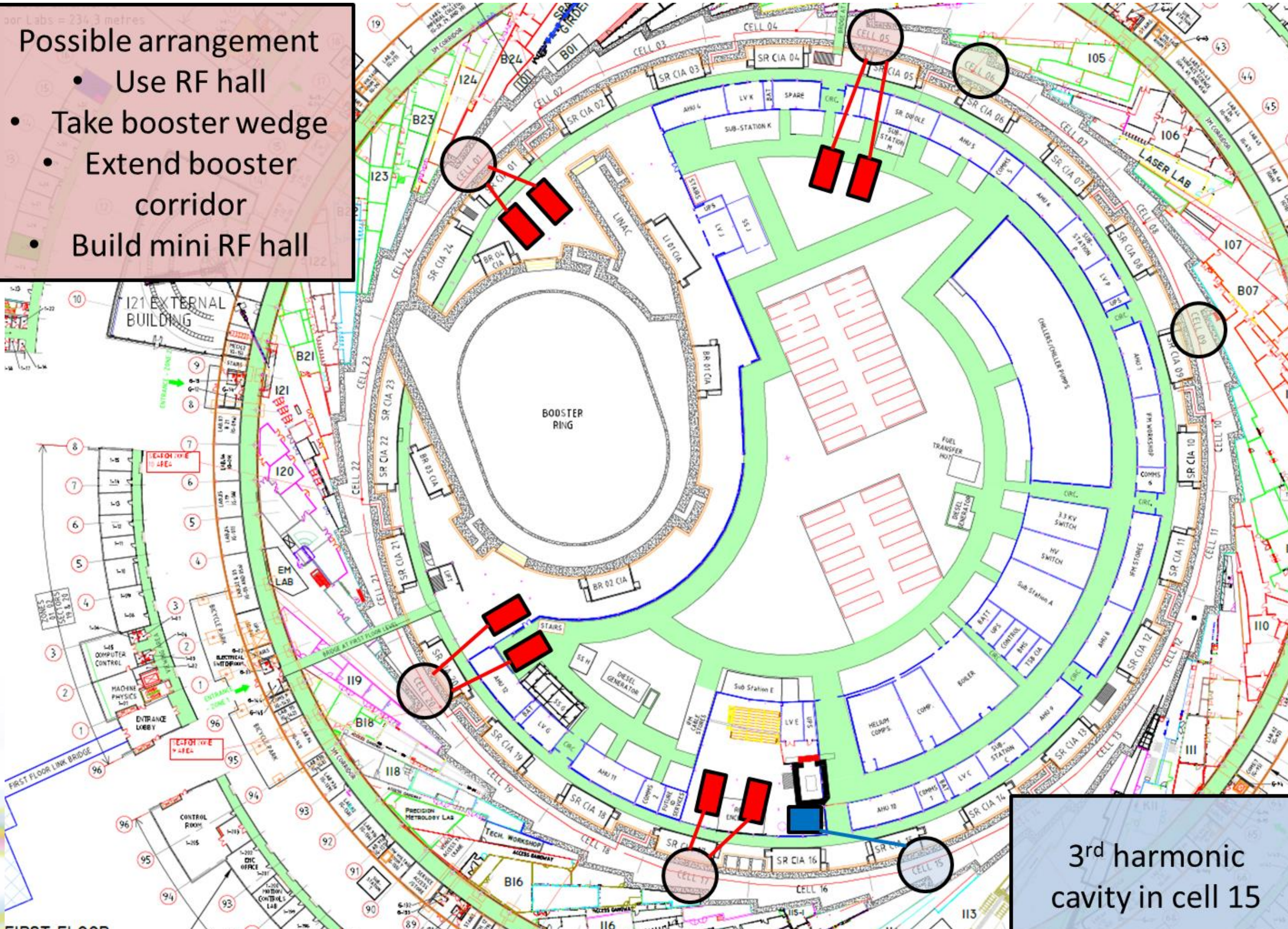


- 2 cavities in two mid-section straights
  - Space for pumps, tapers and valves
  - No front-end problem in mid-section straight after RF straight

- Easier to accommodate NC cavities than SC cavities
  - Front-end supports must be modified
  - Space must be provided for amplifiers (also true for superconducting cavities)
- Alternatively, four pairs of NC cavities could be spread around the ring
  - Present RF straight can be used for new insertion device
  - More space can be devoted to amplifiers

Distributed RF

Possible arrangement
- Use RF hall
- Take booster wedge
- Extend booster corridor
- Build mini RF hall



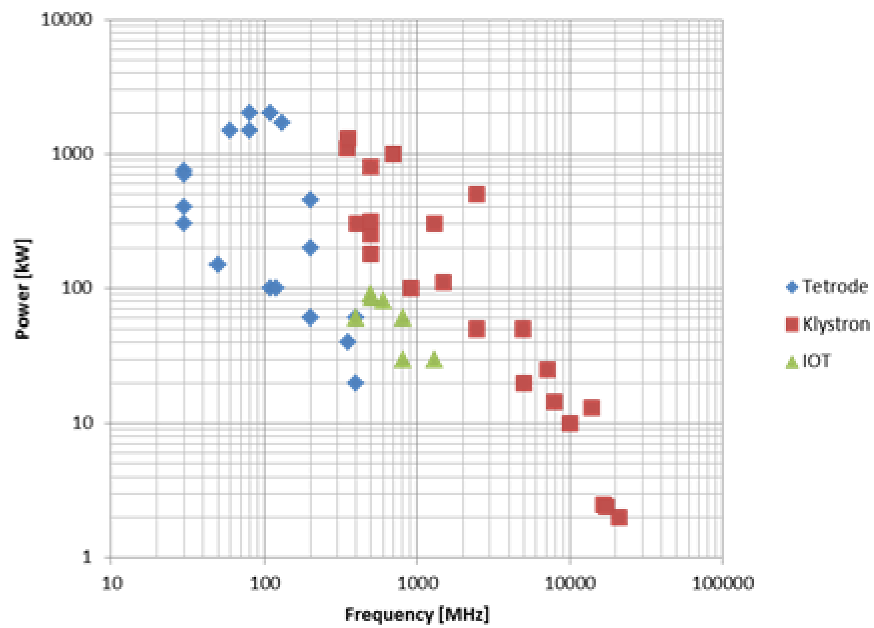
3rd harmonic cavity in cell 15

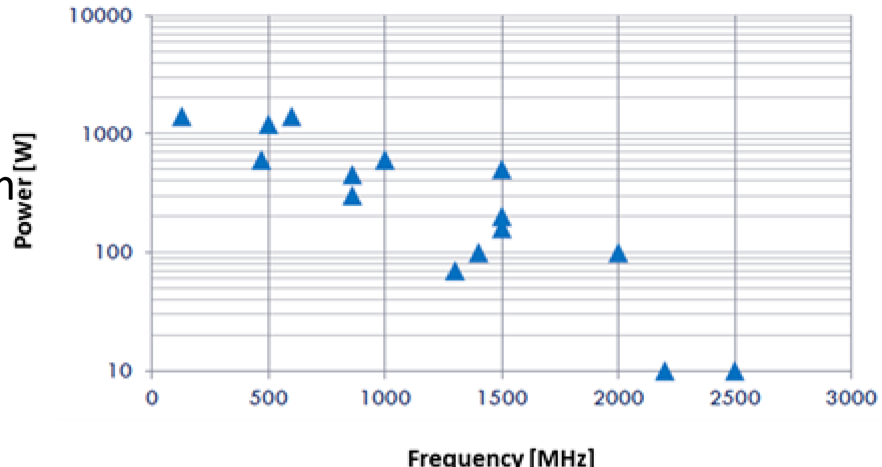
Amplifier type

Vacuum tubes or solid state?

- Vacuum tubes
  - IOTs or klystrons available
  - Proven over many years
  - Tens of kV in HVPS
  - Limited redundancy
  - Obsolescence may become an issue
  - Prices are increasing
  - Slightly higher efficiency

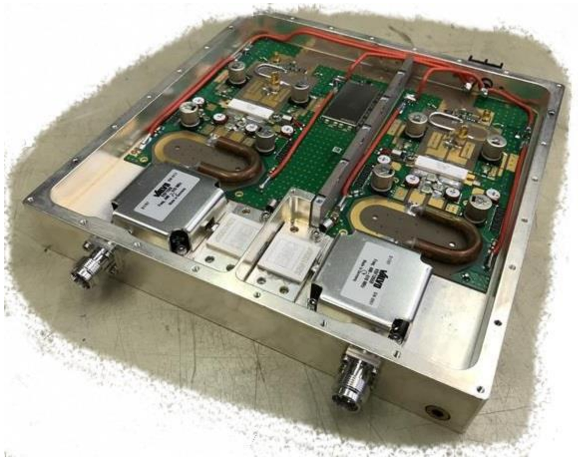
- Solid state amplifiers
  - LDMOS power transistors up to 1kW
  - Several labs now using SSA
  - Typically use 50V supplies
  - Easier to work with and less noise on beam
  - Extreme redundancy for fault tolerance
  - Limited product lifetime but generally replaced by equivalent
  - Prices are decreasing
  - Slightly lower efficiency

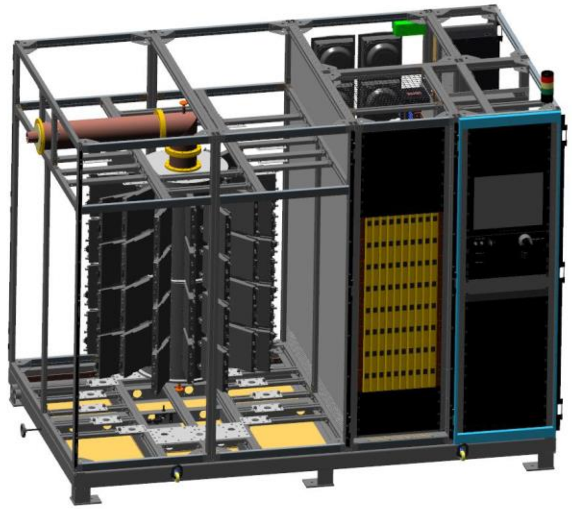


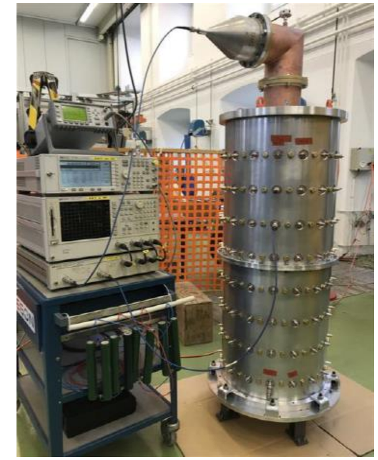


Survey E. Montesinos

High power solid state amplifiers



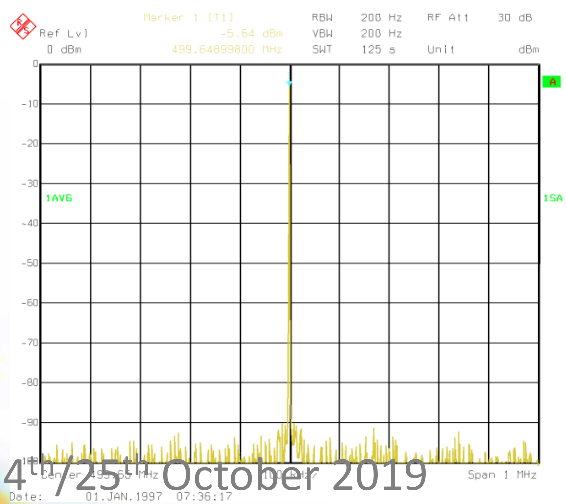


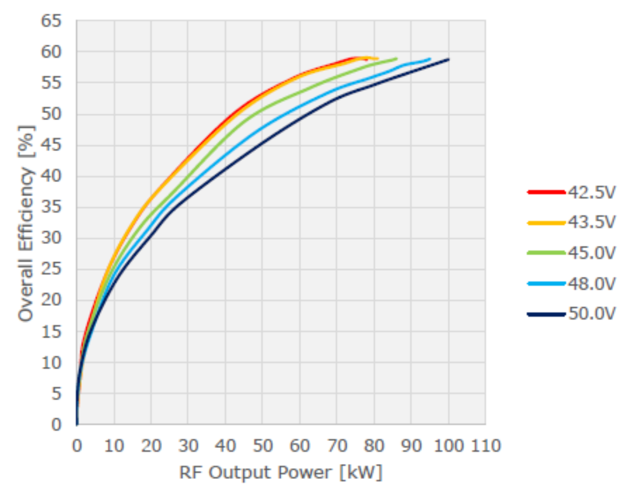


- Ampleon BLF578 50 V LDMOS power transistor
- 2 x 850 W RF out per module
- Built in circulator
- Lowest possible thermal resistance

- 128 port RF cavity combiner
- Combiner is 99% efficient
- Tuneable with >4 MHz 3 dB bandwidth

- > 80 kW output
- > 57% efficiency
- Redundancy demonstrated
- CW, AM and pulsed operation
- Harmonics < 30 dBc
- Spurious emissions <80 dBc





Low level RF: Alba design

Digital low level RF systems have advantages over analogue systems of flexibility and adaptability

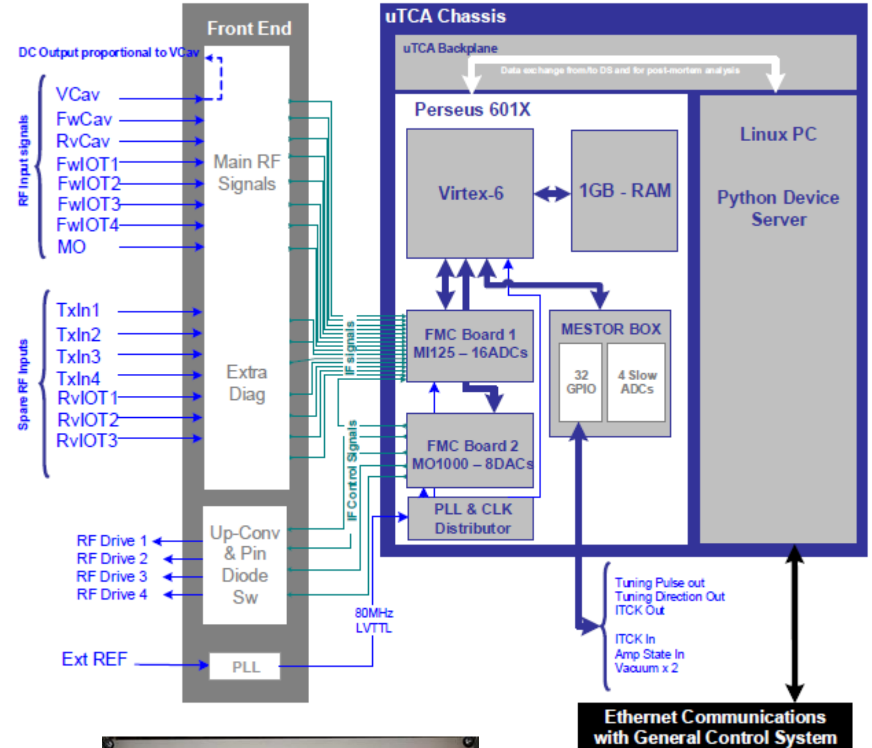
Functionality

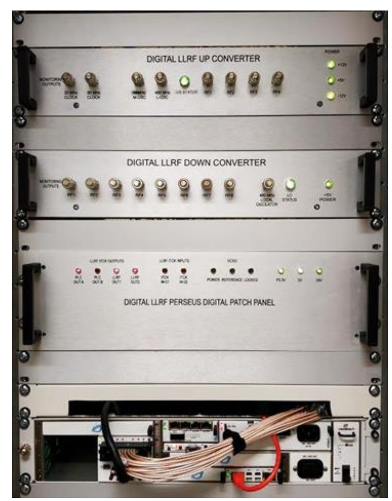
- IQ or polar PI loops of the cavity field for amplitude and phase.
- Cavity tuning
- Fast interlock handling.
- Automatic start-up and conditioning
- Monitoring of RF signals
- Recording of main digital processing signals for post-mortem analysis

Features

- Based on the MicroTCA standard
- Perseus 601X advanced mezzanine card with Virtex6 FPGA
- 16 Channel 14-bit ADCs and 8 channel 16-bit DACs

Recently employed at Diamond





Higher Harmonic Cavity

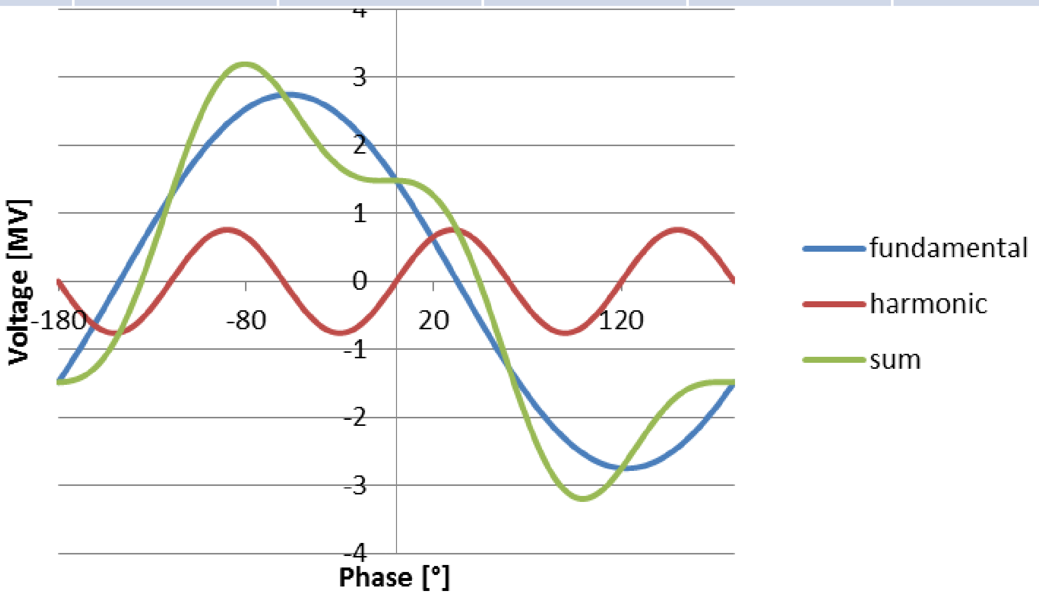
- Higher harmonic cavity is needed for Bunch Lengthening
  - *Alleviate collective instabilities*
  - *Maximise beam lifetime*
  - *Minimise storage ring component heating*
- Used in other machines
  - *Active or passive?*
  - *Superconducting or normal conducting?*

	NSLS II	BESSY II	ELETTRA/ SLS	Max IV	APS-U
SC or NC	SC	NC	SC	NC	SC
Active or passive	passive	passive	passive	passive	passive
Cells	2	4 x 1 cell	2	3 x 1 cell	1
Frequency	1.5 GHz	1.5 GHz	1.5 GHz	300 MHz	1.4 GHz
Typical voltage	860 kV	400 kV	600 kV	170 kV	900 kV

- Optimal amplitude and phase to flatten potential

$$k_{fp} = \sqrt{\frac{1}{n^2} - \frac{1}{n^2-1}\left(\frac{U}{e_0 V_{rf}}\right)^2}$$

$$\tan(n\phi_{hfp}) = -\frac{\frac{nU}{e_0 V_{rf}}}{\sqrt{(n^2-1)^2 - \left(n^2 \frac{U}{e_0 V_{rf}}\right)^2}}$$



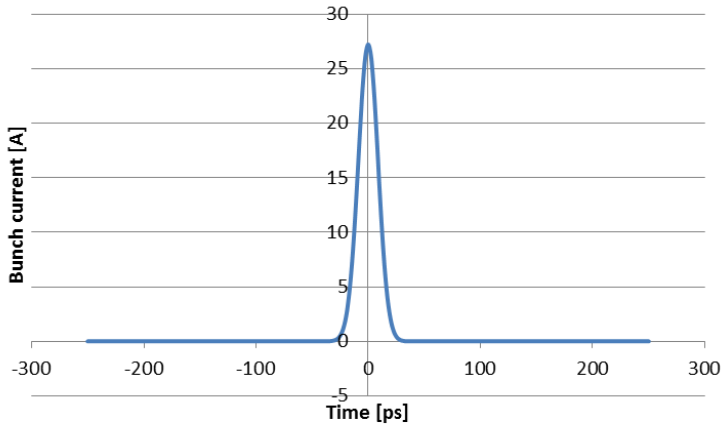
Higher Harmonic Cavity design

	Passive NC	Active NC	Passive SC
Advantages	Simple	Allows operation at optimal voltage and phase for any beam current	Operates to low current Less sensitive to filling pattern Less sensitive to Robinson instability as bandwidth is small and detune is near 90°
Disadvantages	Optimal operation only at one beam current Gap in fill pattern induces strong modulation which reduces effectiveness Operation well into the Robinson unstable slope	RF amplifier required Gap in fill pattern induces strong modulation which reduces effectiveness Operation well into the Robinson unstable slope	Cryogenic system required Narrow bandwidth means cavity is harder to control

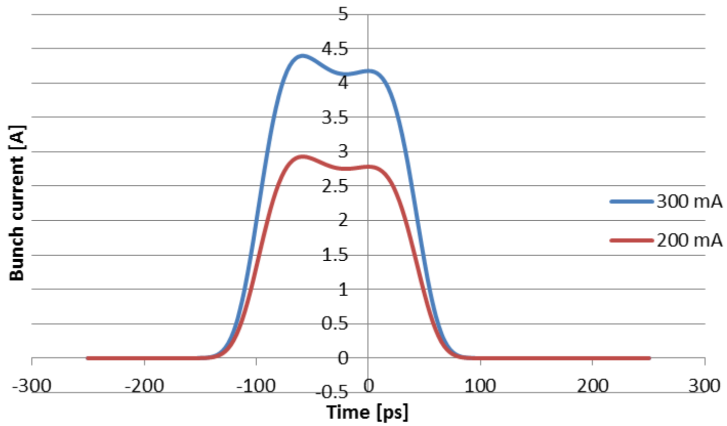
- Select passive superconducting third harmonic cavity
  - Using cryogenic plant for Diamond
  - Detune is almost constant for all conditions allowing wide range of operating currents
  - Robinson destabilisation is small and can be damped by fundamental cavity detune
  - Two designs available at 1.5GHz
    - ELETTRA/SLS years of operation
    - NSLS II not fully proven

Higher Harmonic Cavity operation

300mA full fill: HHC fully detuned



HHC: 48kHz@300mA 32kHz@200mA



- Diamond cryogenic plant
  - Air Liquide Helial 2000
  - Closed loop refrigerator
  - Design performance of 488W
  - Measured performance of 500W plus 20 litres/hr
    - PSI 3HC requires 50W and 5 litres/hr
  - Cavity will fit in mid section straight
    - Select location to minimise distance to cryogenic plant

Summary

- Conceptual design has been identified
  - 500MHz RF frequency
  - 8 normal conducting cavities
  - 8 solid state amplifiers
  - Digital LLRF in microTCA format
  - Passive superconducting third harmonic cavity

- Next steps
  - Advance conceptual design
  - Working on linac and booster RF upgrade requirements

Thank you for your attention