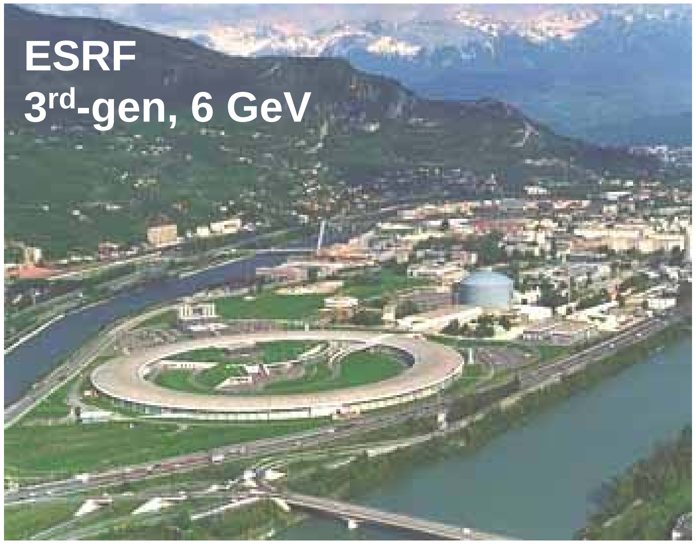
4GLS and ERLP at Daresbury

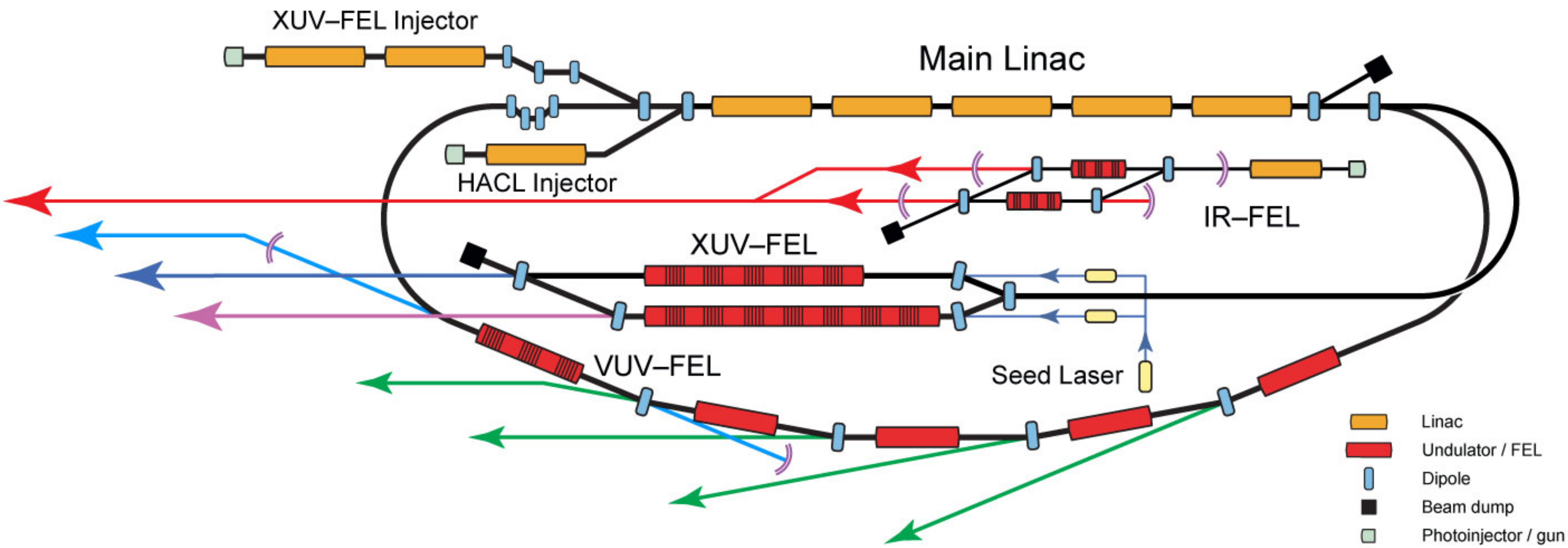
Hywel Owen
Accelerator Science and Technology Centre

UK Synchrotron Radiation Provision

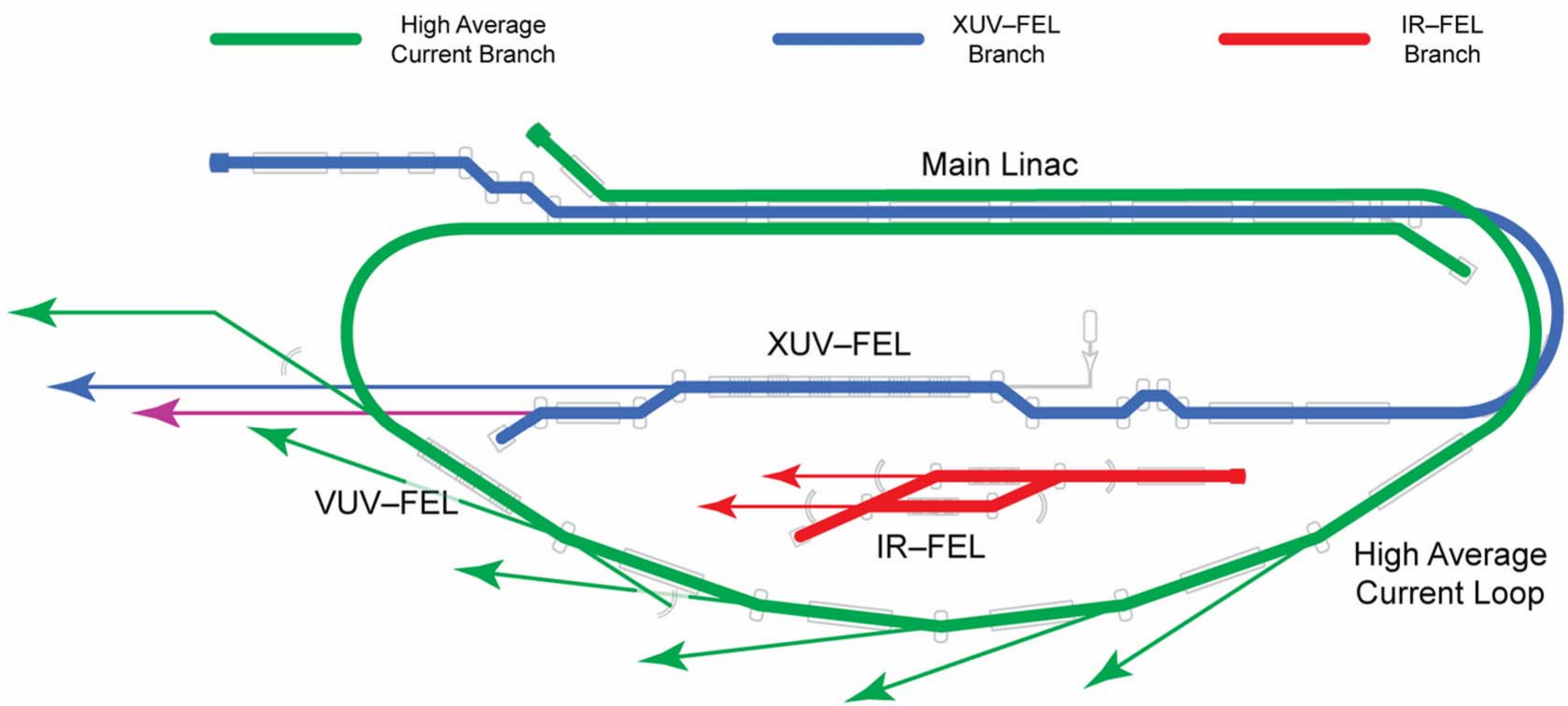


- The UK wants a suite of IR to XUV short-pulse sources to complement what is available to UK users.

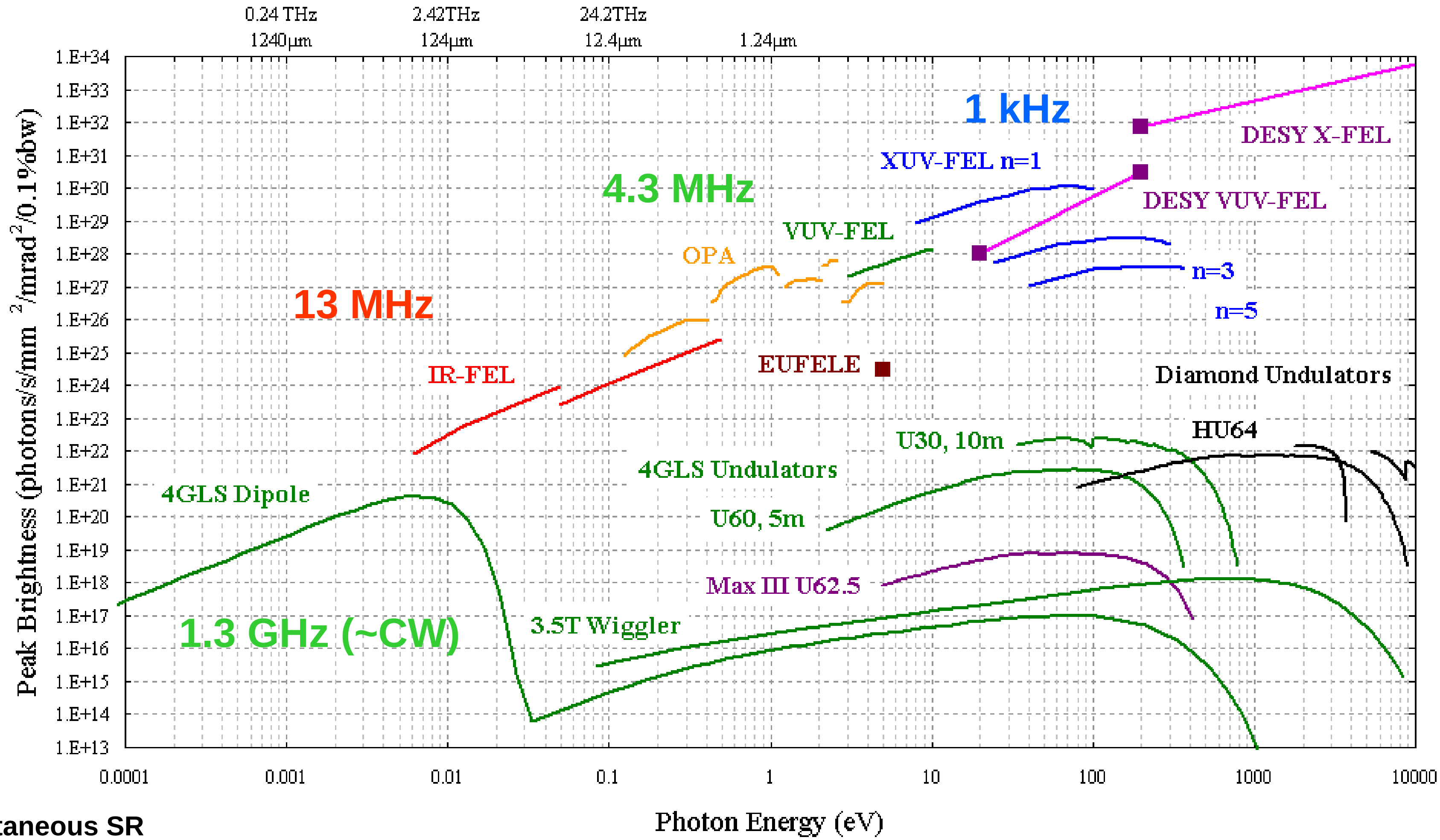
The 4GLS Concept



4GLS Branches and Bunch Paths



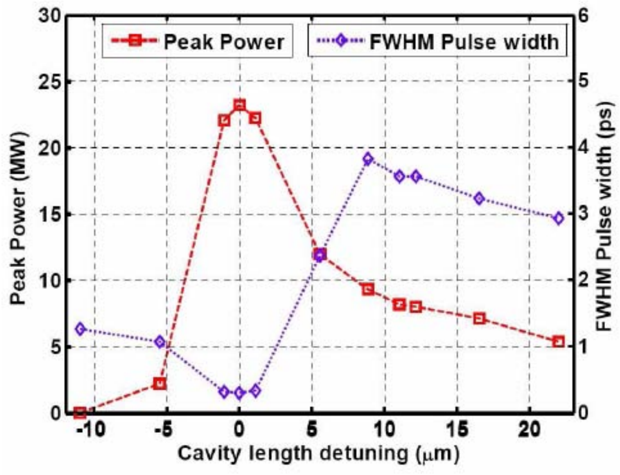
4GLS: Photon Output Coverage and Repetition Rates

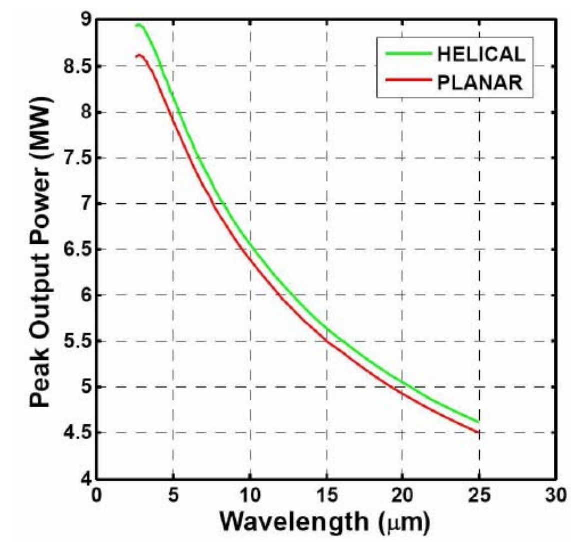


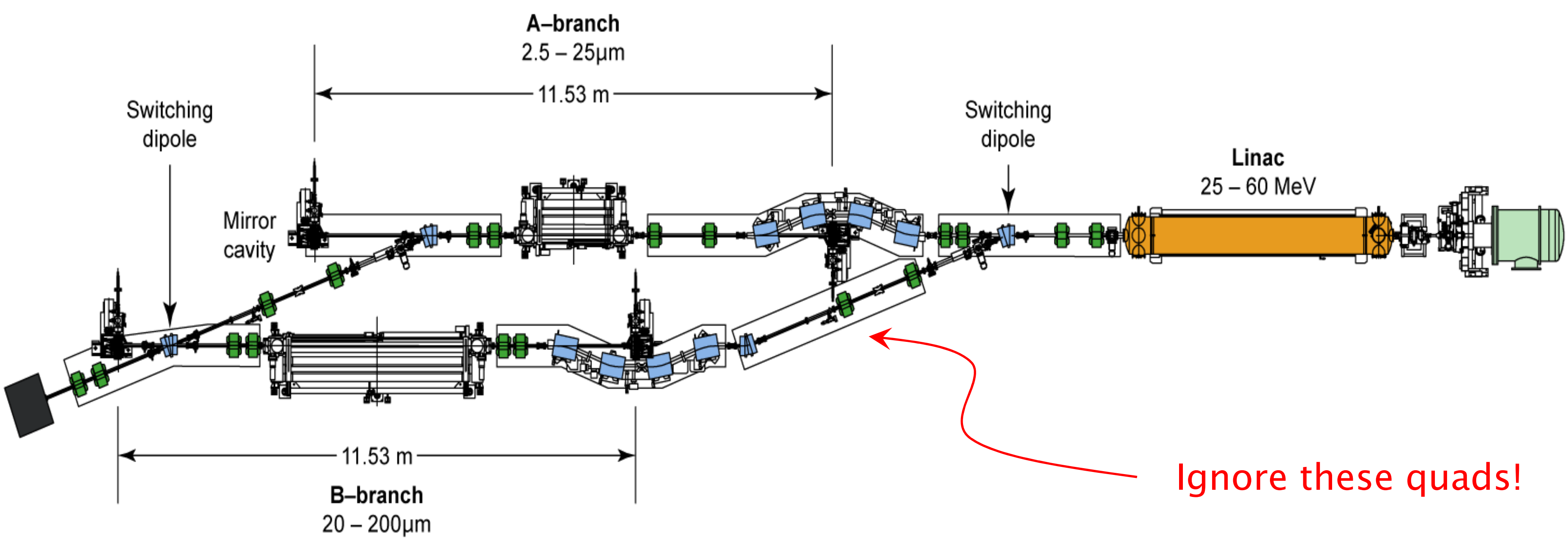
Spontaneous SR
Range: up to 1keV
Pulse length: few ps down to 100 fs
Repetition rates: 1.3 GHz/6.5 MHz/1 kHz

4GLS IR-FEL

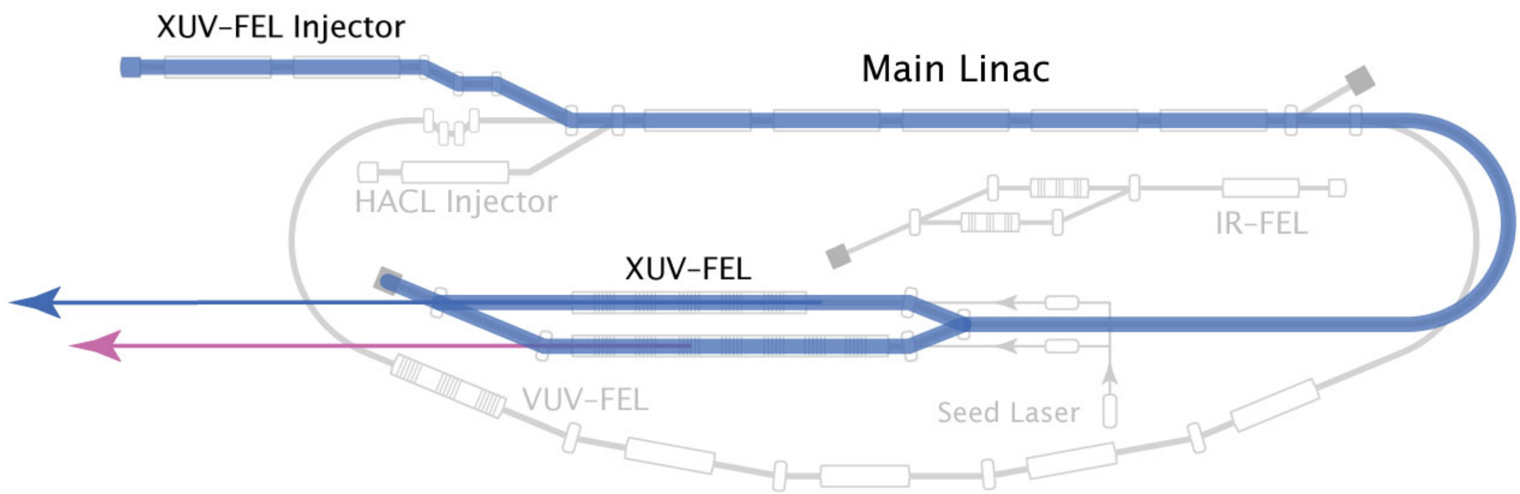
- 2.5 to 200 μm
- Oscillator FEL
- SCRF for stability
- 25 to 60 MeV
- Investigating new request for 2 simultaneous IR FEL Beams





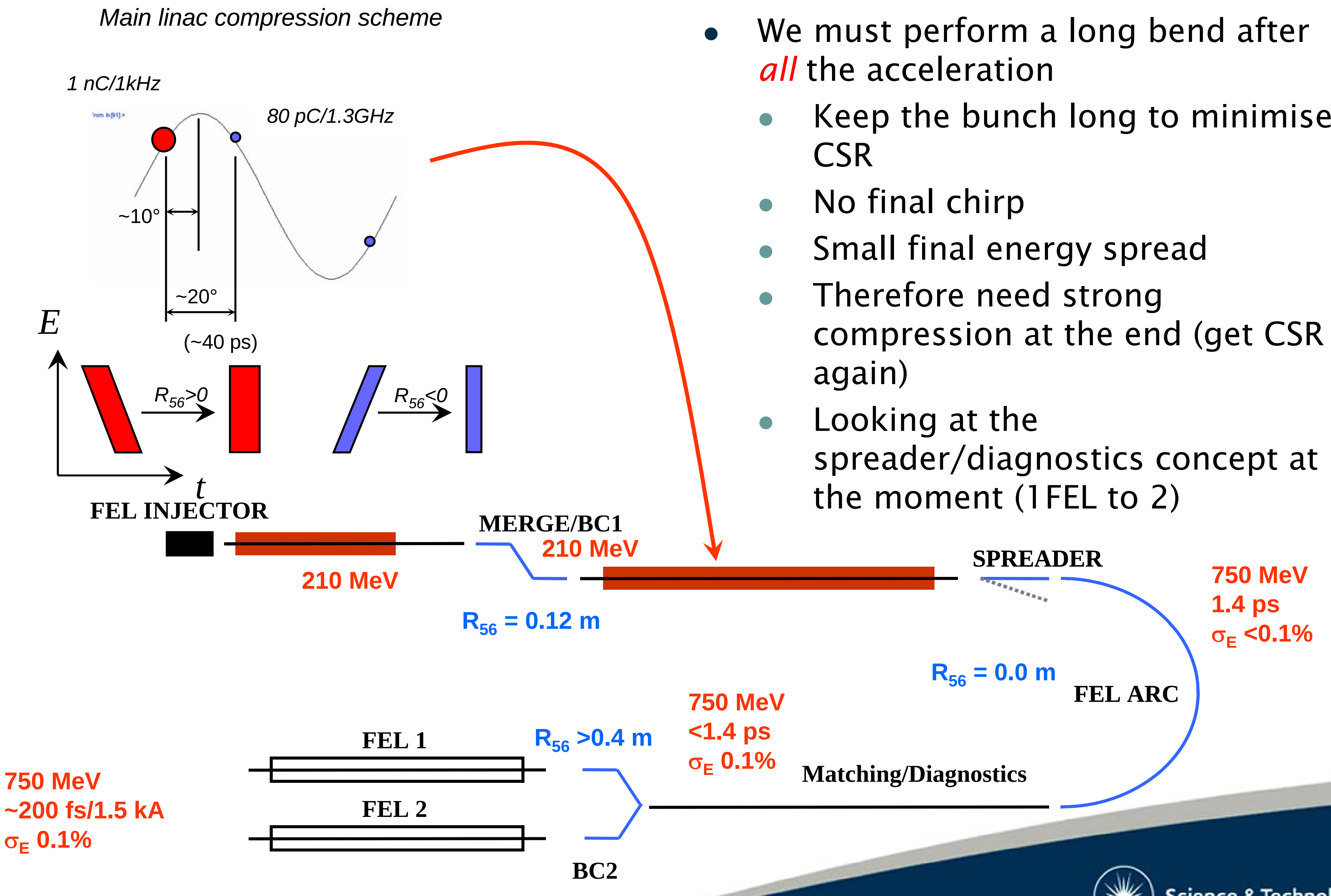


XUV-FEL Branch



1 nC, 750 MeV, 2 mm mrad normalised emittance, 1 kHz, 1.5 kA

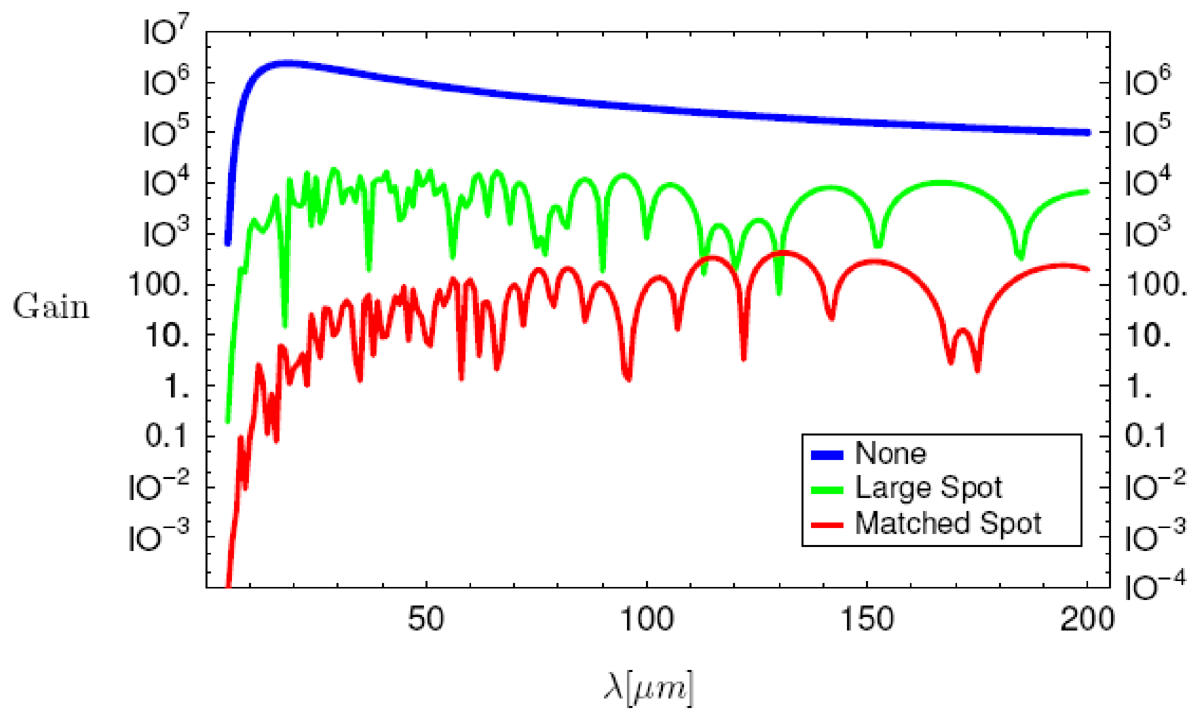
XUV-FEL Compression Scheme



- We must perform a long bend after *all* the acceleration
  - Keep the bunch long to minimise CSR
  - No final chirp
  - Small final energy spread
  - Therefore need strong compression at the end (get CSR again)
  - Looking at the spreader/diagnostics concept at the moment (1FEL to 2)

XUV-FEL Microbunching

Parameter	First Bunch Compressor	Second Bunch Compressor
Compression Factor	3	12
E [MeV]	200	750
I_f [A]	125	1500
$\gamma\epsilon_0$ [μm]	1.8	2.5
β_0 [m]	15	15
α_0	1	1
σ_δ	2×10^{-5}	5.3×10^{-6}
h [m^{-1}]	-4.44	-1.31
R_{56} [m]	0.15	0.70
ρ_0 [m]	1.51	1.51
L_b [m]	0.4	1
ΔL [m]	0.8	2

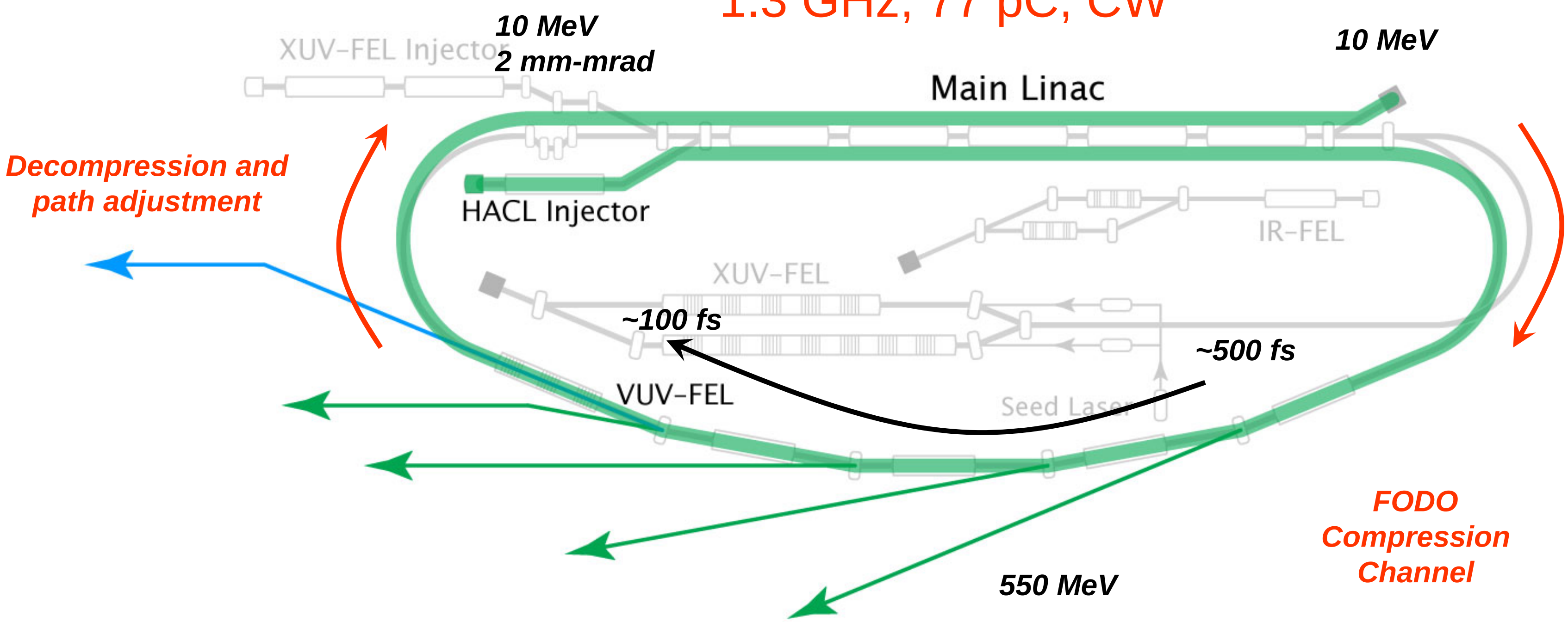


Z. Huang and Peter Williams

High Average Current Loop – the ERL part

100mA, 550 MeV, 2 mm-mrad normalised emittance

1.3 GHz, 77 pC, CW



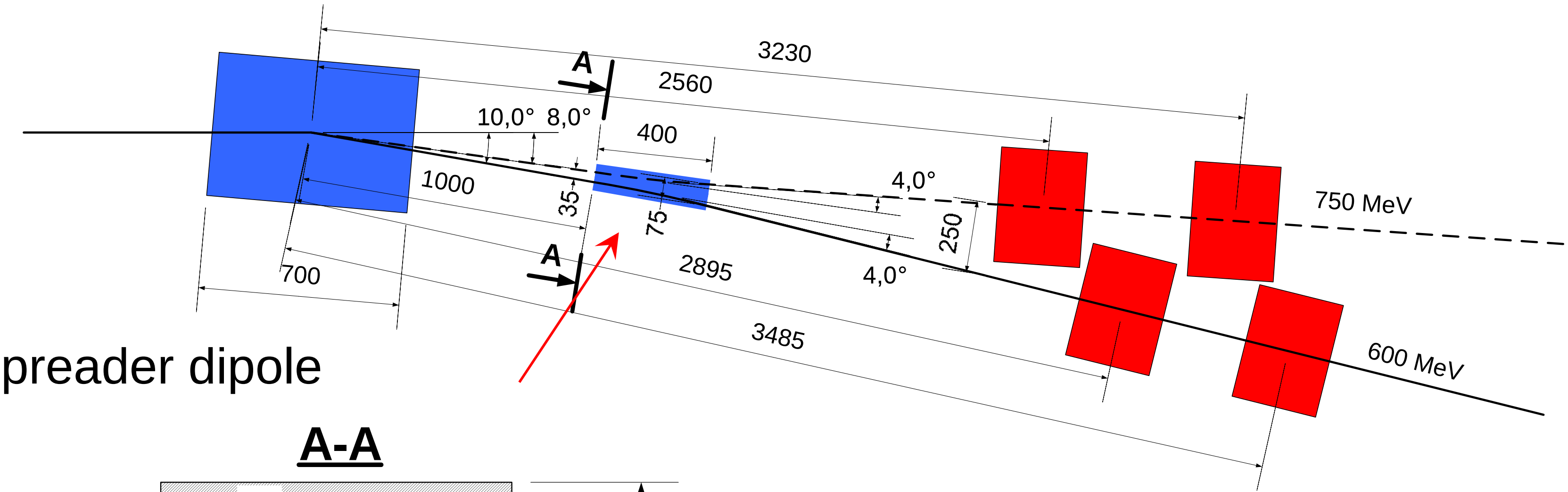
Undulator sources + VUV-FEL

Progressive compression, ~500 fs to 100 fs

4GLS Parameters (Present Configuration)

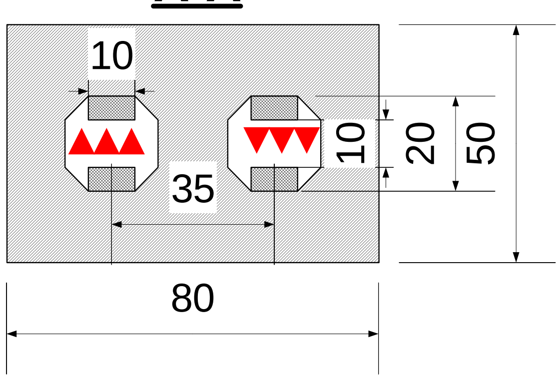
Bunch Parameter	*XUV-FEL*	*100 mA HACL Operation*	*VUV-FEL HACL Operation*	*IR-FEL*
Electron Energy (MeV)	**750**	**550**	**550**	**25 to 60**
Normalised Emittance (mm mrad)	2	2	2	10
RMS Projected Energy Spread	0.1 %	0.1 %	0.1 %	0.1 %
RMS Bunch Length	< 270 fs	**100 to 900 fs**	100 fs	1 to 10 ps
Bunch Charge	**1 nC**	**77 pC**	**77 pC**	**200 pC**
Bunch Repetition Rate	**1 kHz**	**1.3 GHz**	**n x 4.33 MHz**	**13 MHz**
Electron Beam Average Power	<1 kW	**55 MW**	n x 183 kW	<156 kW

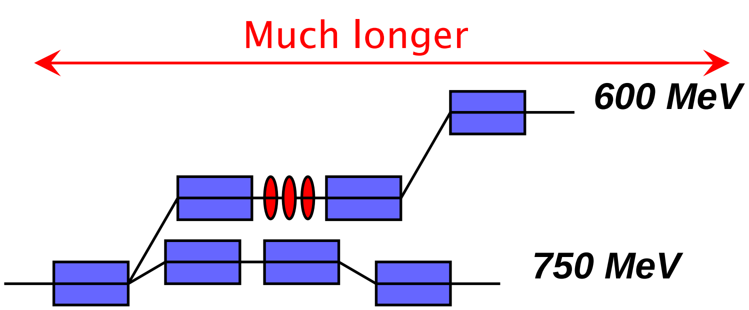
Beam Separation Concept



Spreader dipole

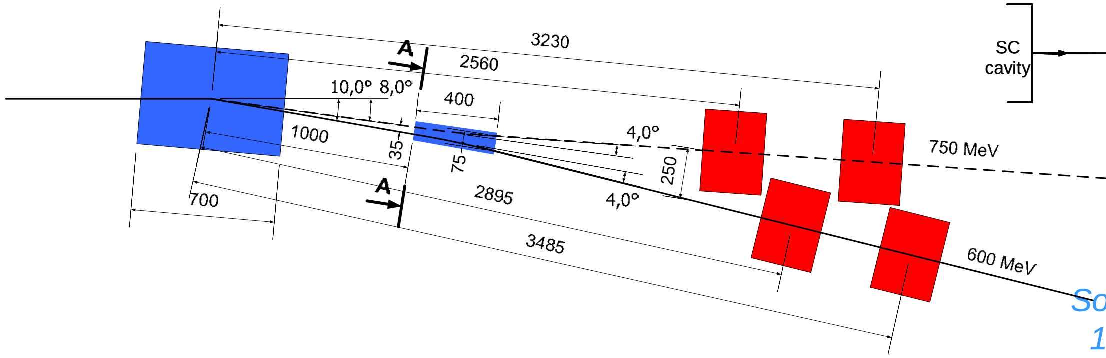
A-A



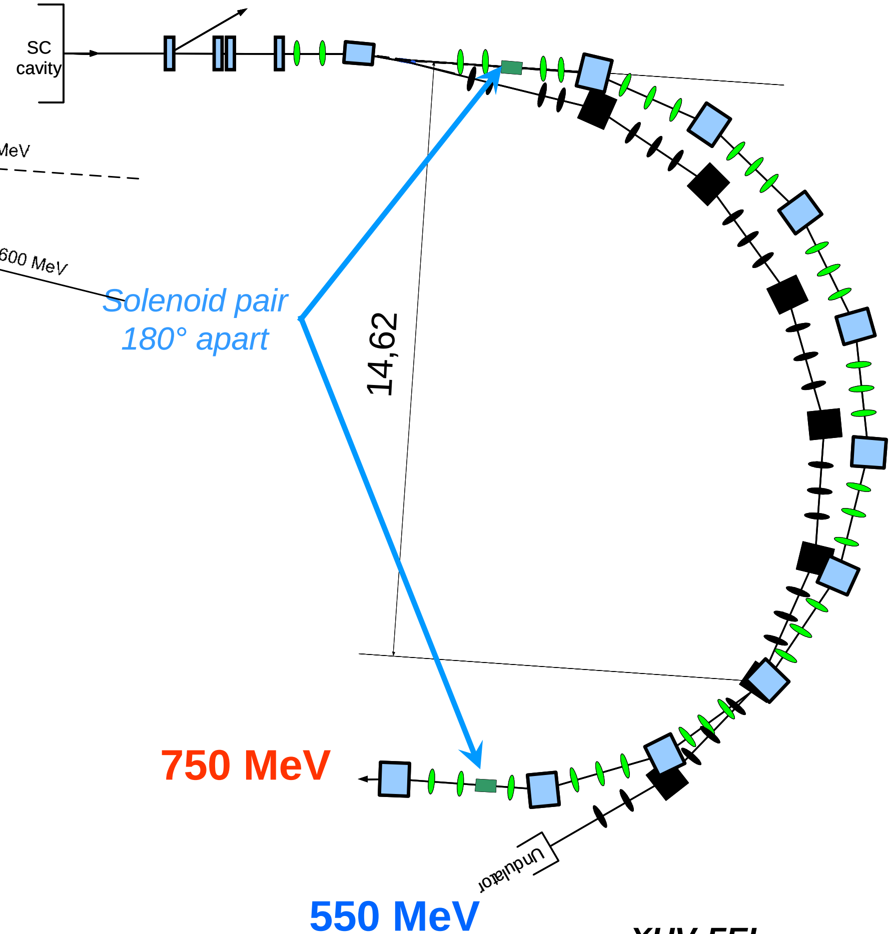


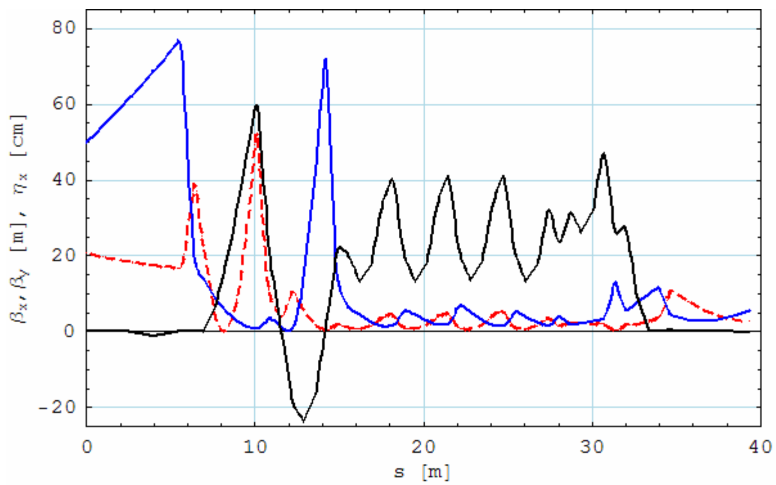
- Spectrometer + spreader dipole
  - (instead of septa or chicane/slide)
- Single (possibly PM) dipole with opposing fields in each aperture
  - cf. LHC dipoles
- Needs engineering study and consideration of beam loss/radiation damage

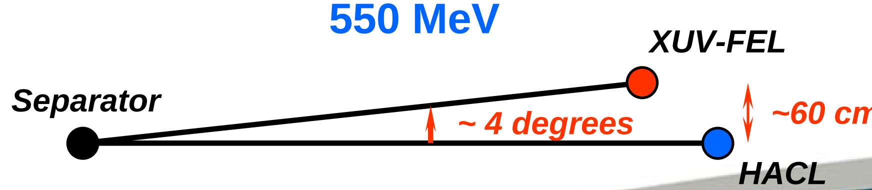
XUV/HACL Outward Arc Transport



HACL/XUV-FEL Magnetic Separator

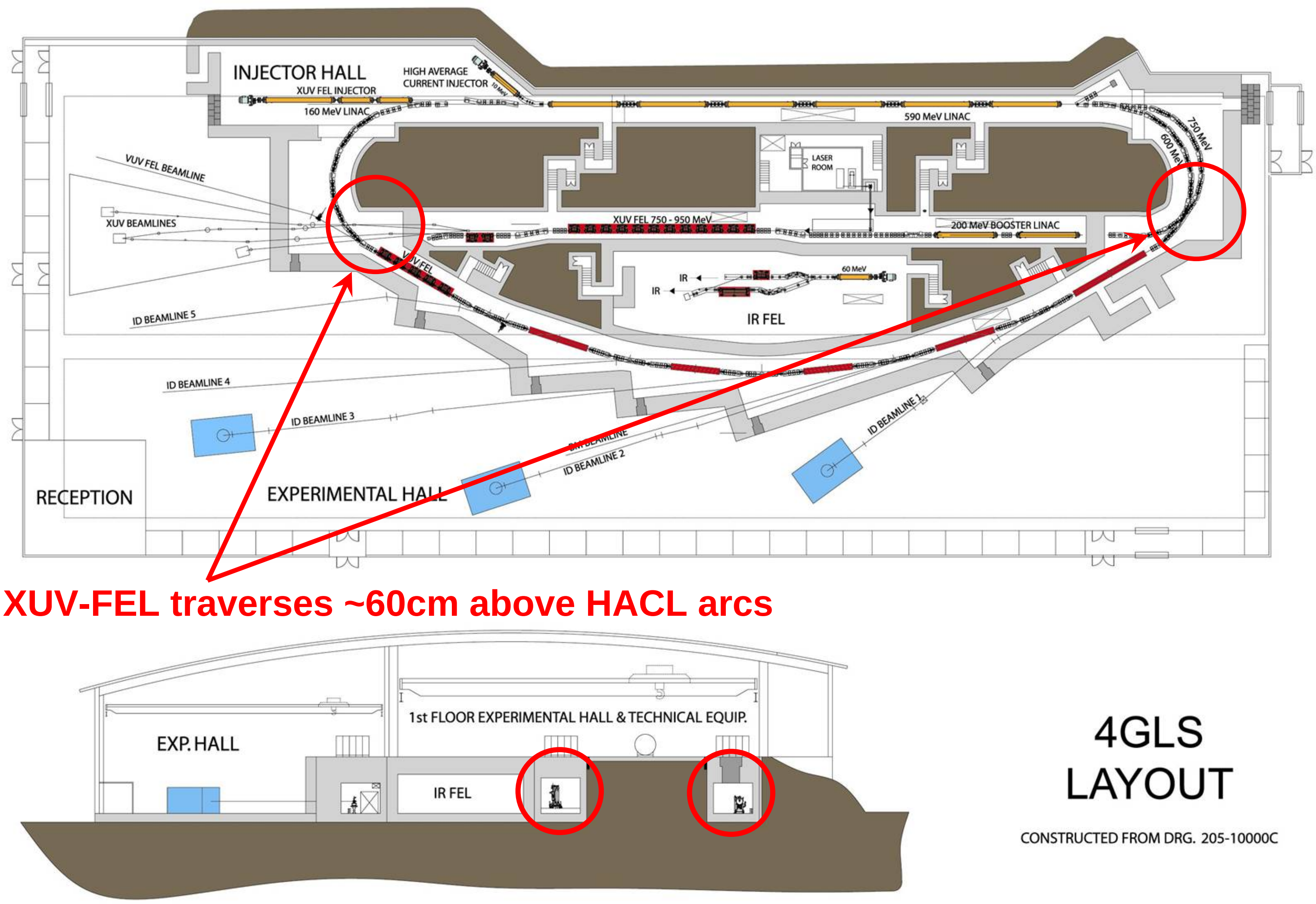






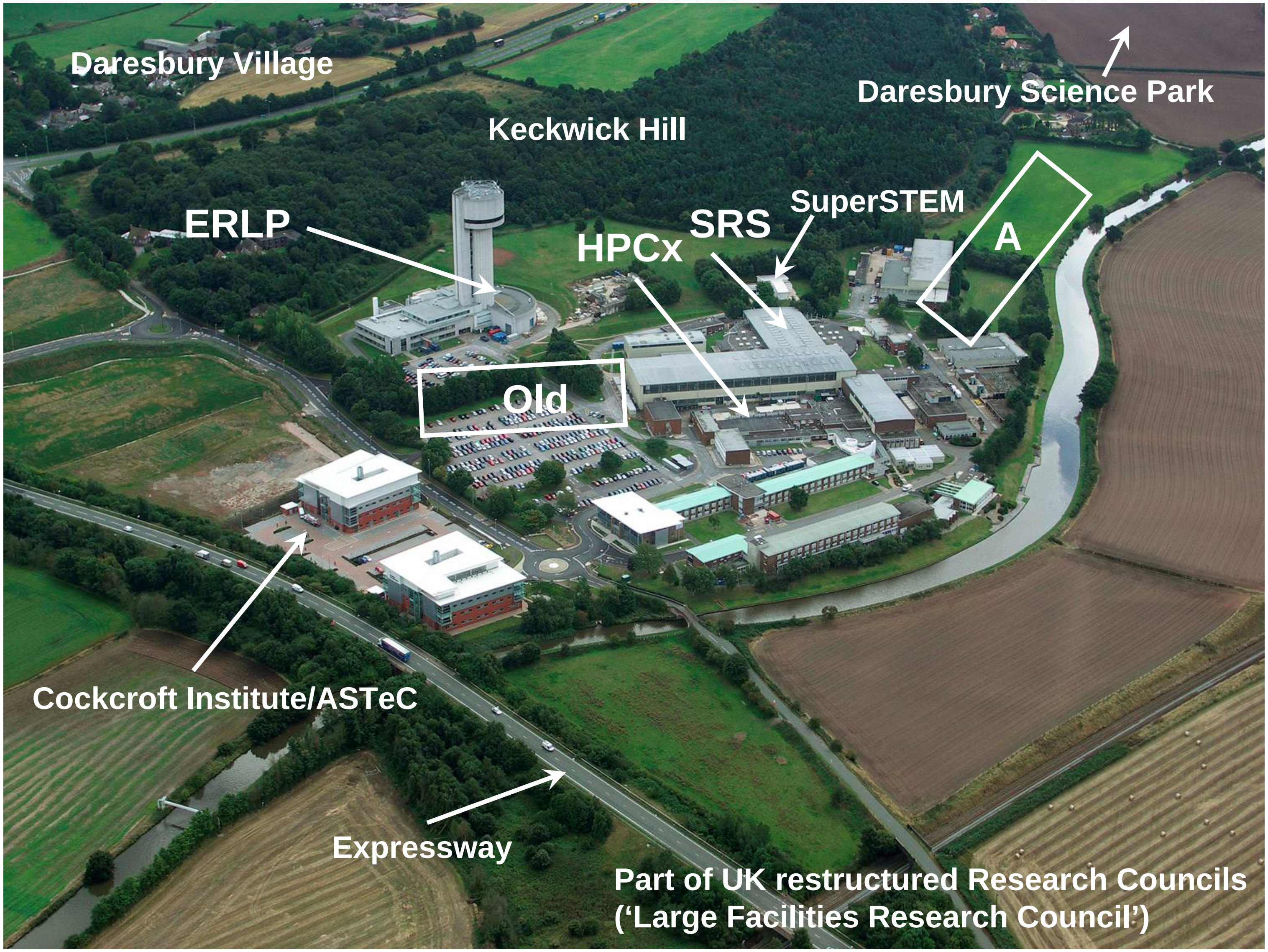
Science & Technology Facilities Council

4GLS – Engineering Concept for XUV and HACL Transport

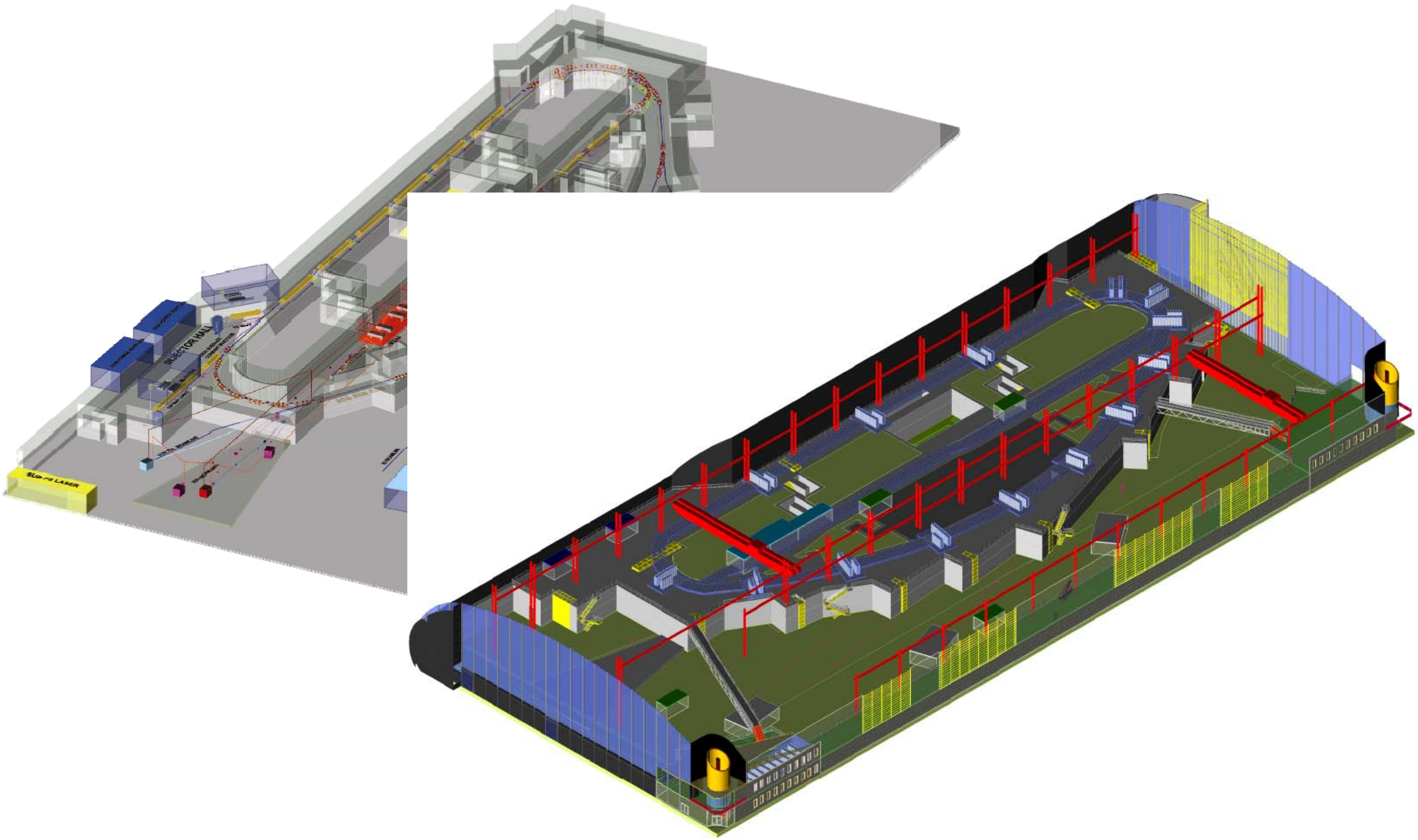


XUV-FEL traverses ~60cm above HACL arcs

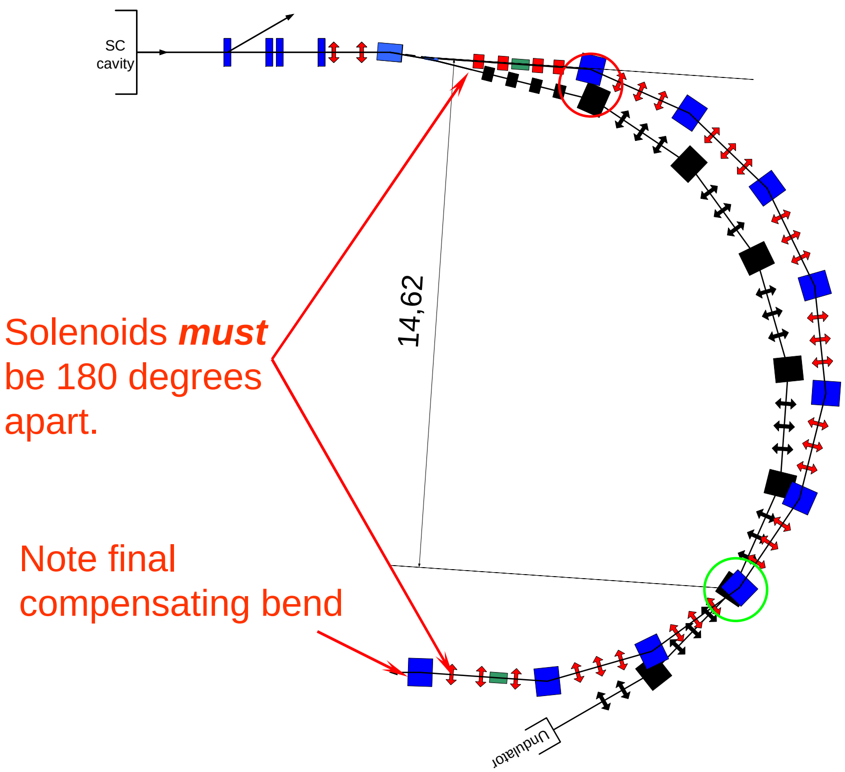
4GLS Possible Sites



4GLS Building Concept



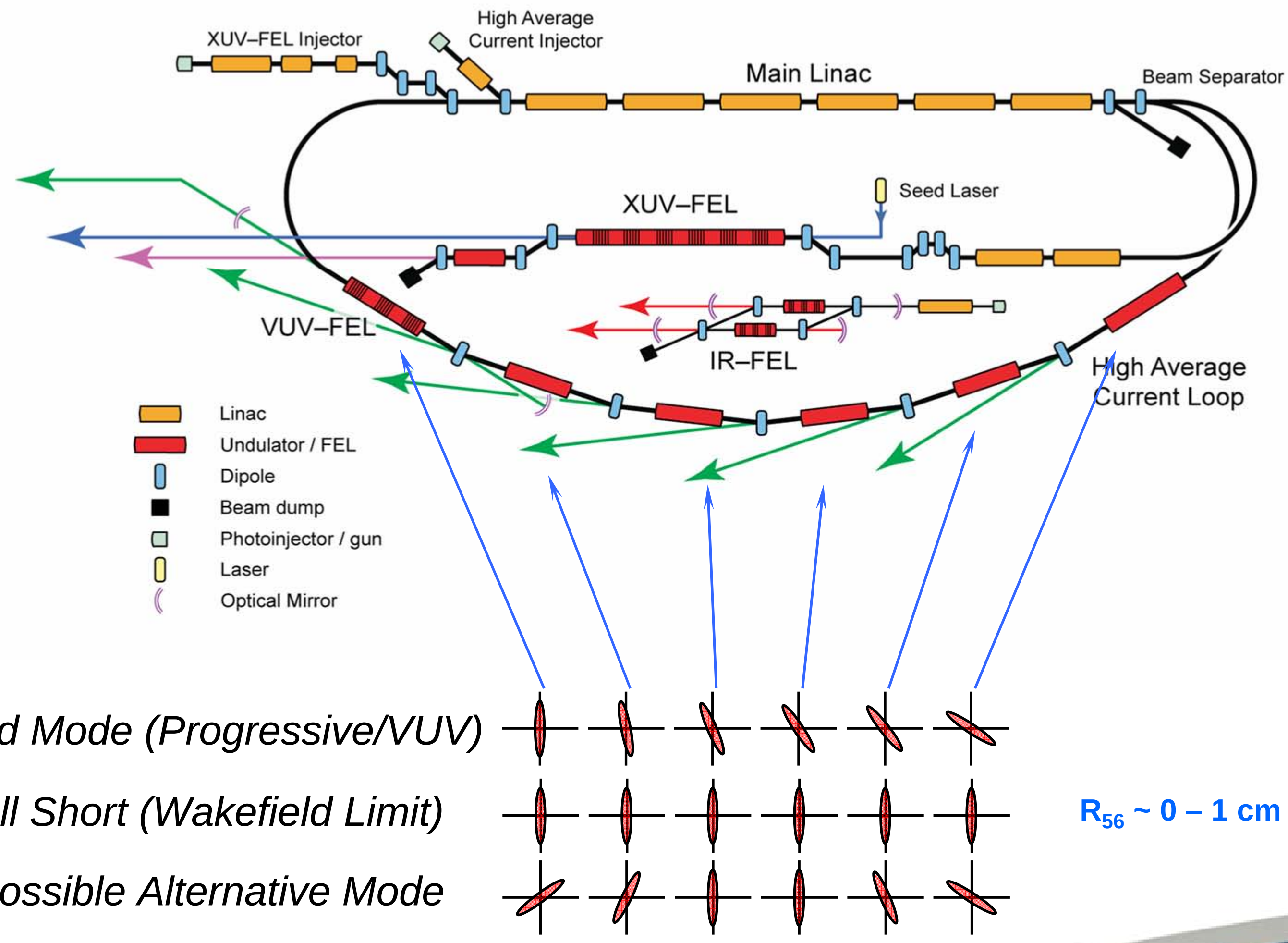
Outward Arc Transport



- FEL arc decompresses
- HACL arc compresses

- Building size restrictions/cost mean:
  - FEL arc outside of CW arc
- Advantages:
  - Keeps FEL arc radius large for CSR management
  - Eliminates opposing bends
- Disadvantages:
  - Vertical offset to transport to pass FEL arc over CW loop arc – 60 cm in present iteration
  - Uses solenoids to achieve vertical matching – no flat beams for FEL branch
  - Optically complex!

HACL Progressive Compression Concept (CDR Configuration)



R_{56} ~ 0.5 m

Standard Mode (Progressive/VUV)

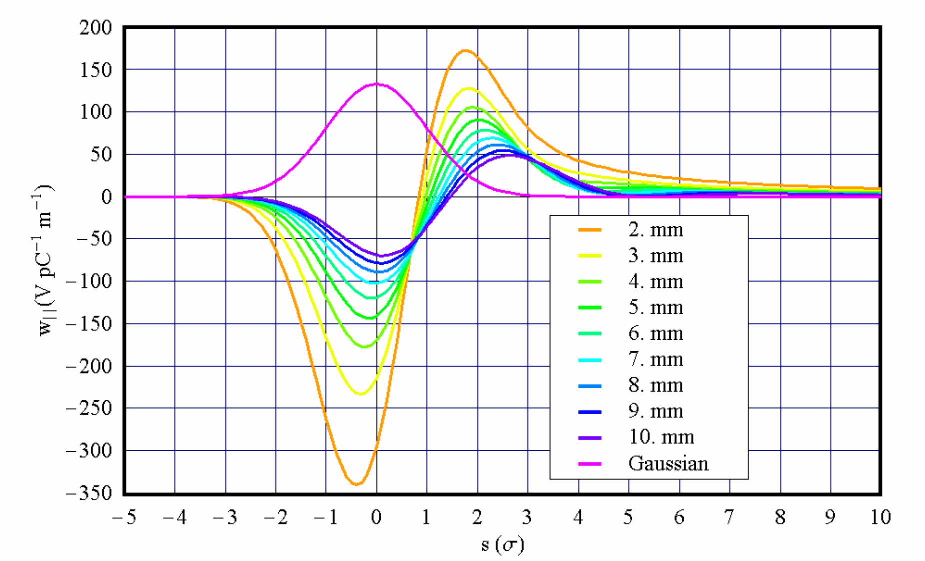
All Short (Wakefield Limit)

Possible Alternative Mode

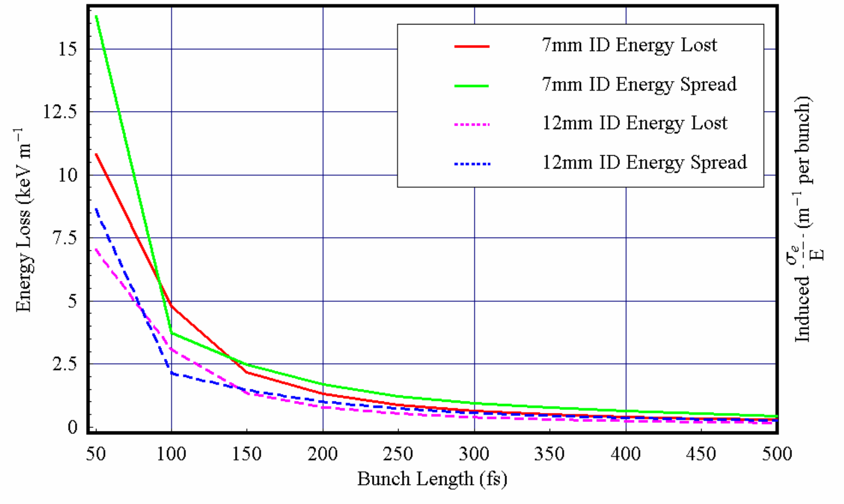
R_{56} ~ 0 – 1 cm per cell

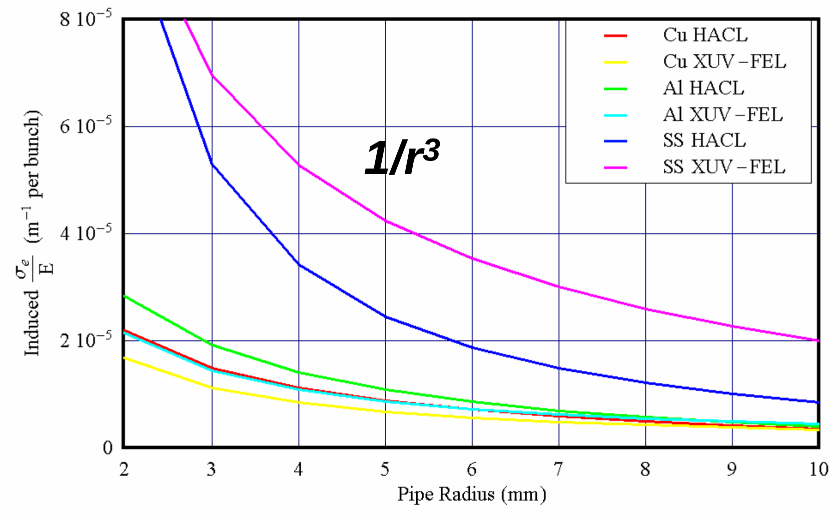
Resistive Wall Wakefields

Cu, 1 nC, 50 fs

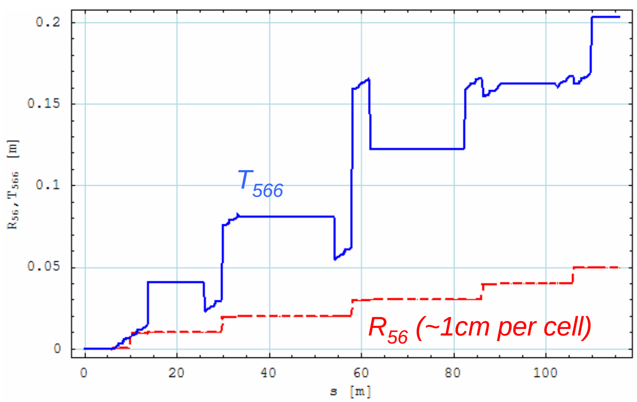


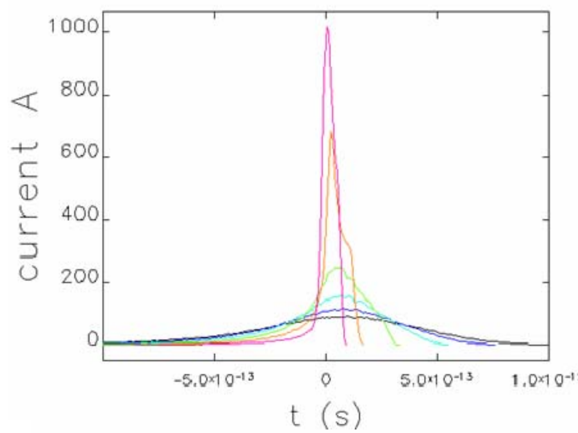
(In reality bunches will not be Gaussian)

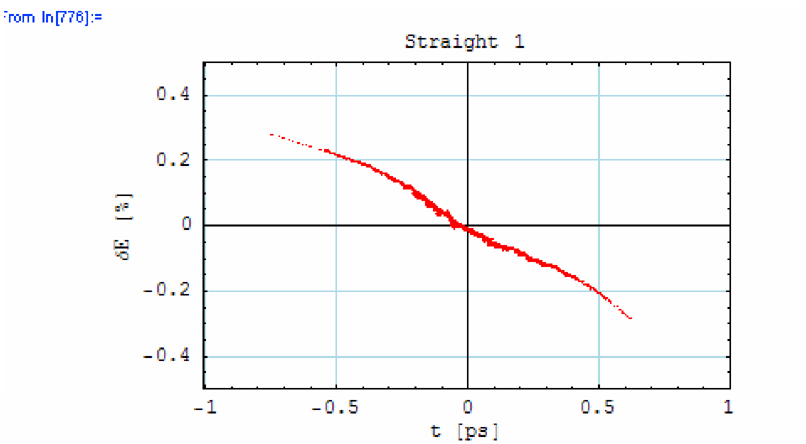


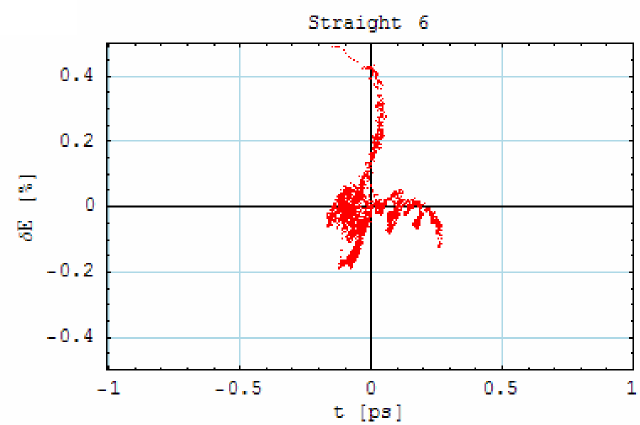


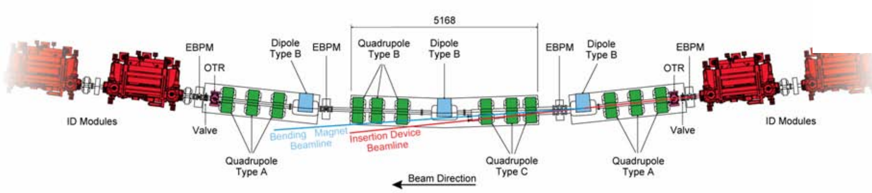
HACL Pseudo-S2E Simulation (CDR Configuration)

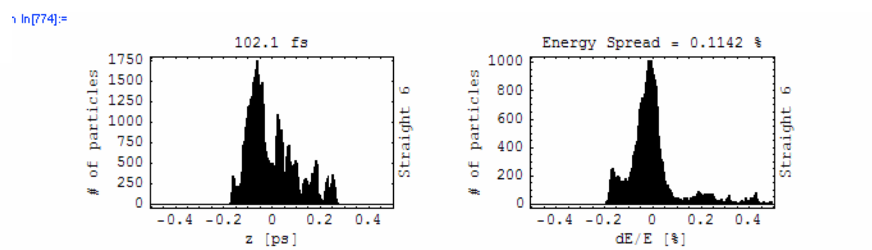








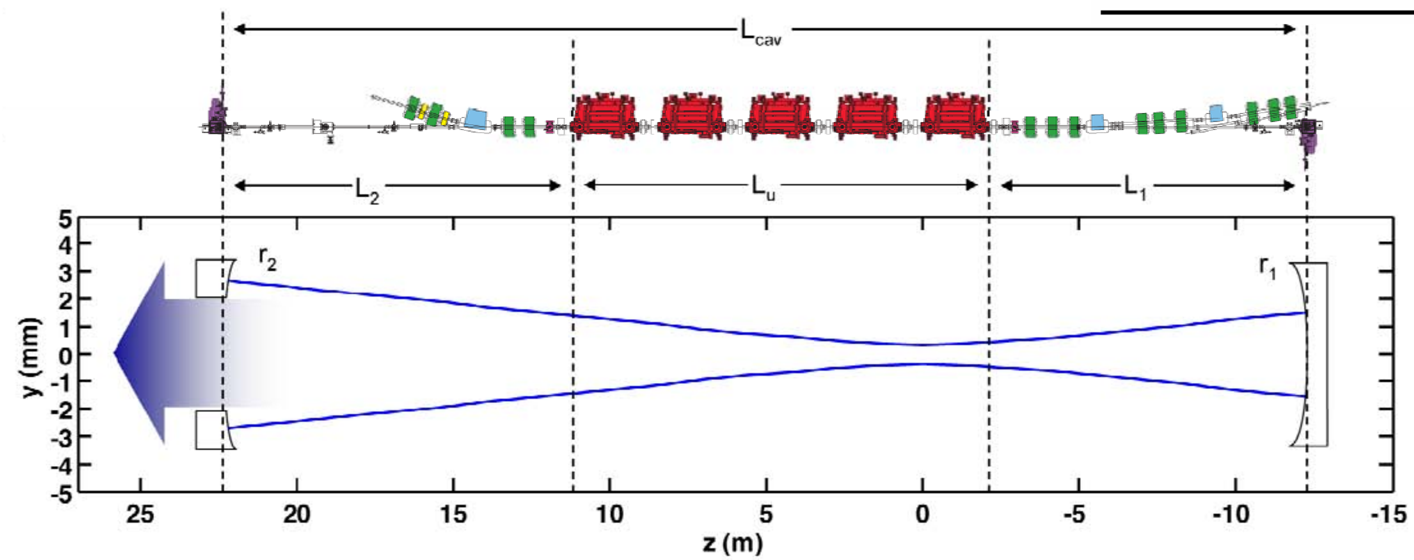




4GLS VUV-FEL

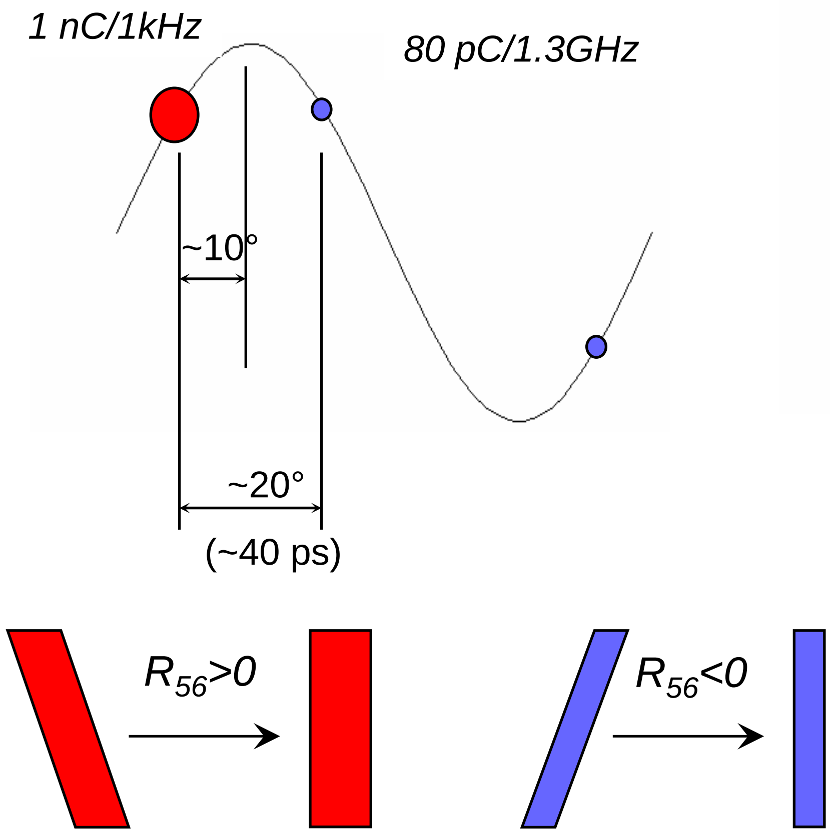
- 3 to 10 eV, ~500MW output
- Regenerative Amplifier system
- 4.33 MHz compared with 1 kHz XUV FEL
- Very tolerant to mirror degradation
- Reflectivity only 40 to 60% needed
- No seed
- 300 A peak current

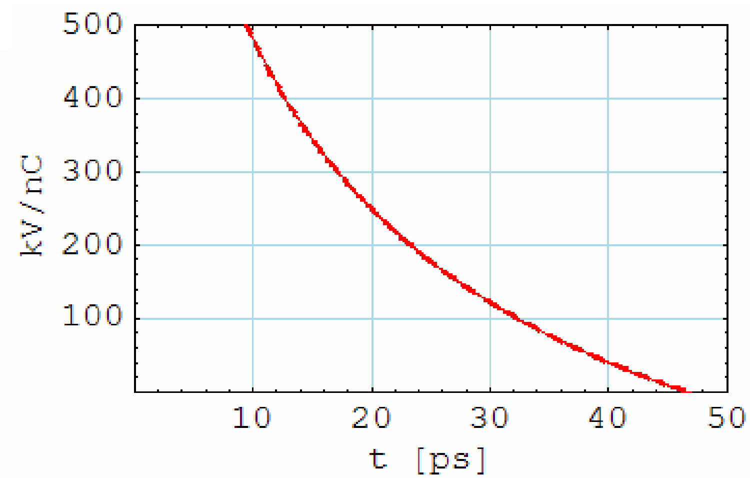
Undulator	
Undulator Period λ_w	60 mm
Periods per module	37
Number of modules	5
Electron Beam	
Electron Beam Energy	600 MeV
Relative Energy Spread (rms)	0.1 %
Bunch Charge	80 pC
Peak Current	300 A
Normalised emittance	2 mm-mrad
Optical Cavity	
Cavity length L_{cav}	34.6 m
Upstream ROC r_1	12.85 m
Downstream ROC r_2	22.75 m
Rayleigh length z_R	2.8 m
Fundamental mode waist w_0	0.34 mm
Waist position (measured from US mirror)	12.2 m
Outcoupling hole radius	2 mm
Cavity stability $g_1 \times g_2$	0.88



4GLS Dual-Phase Compression Concept

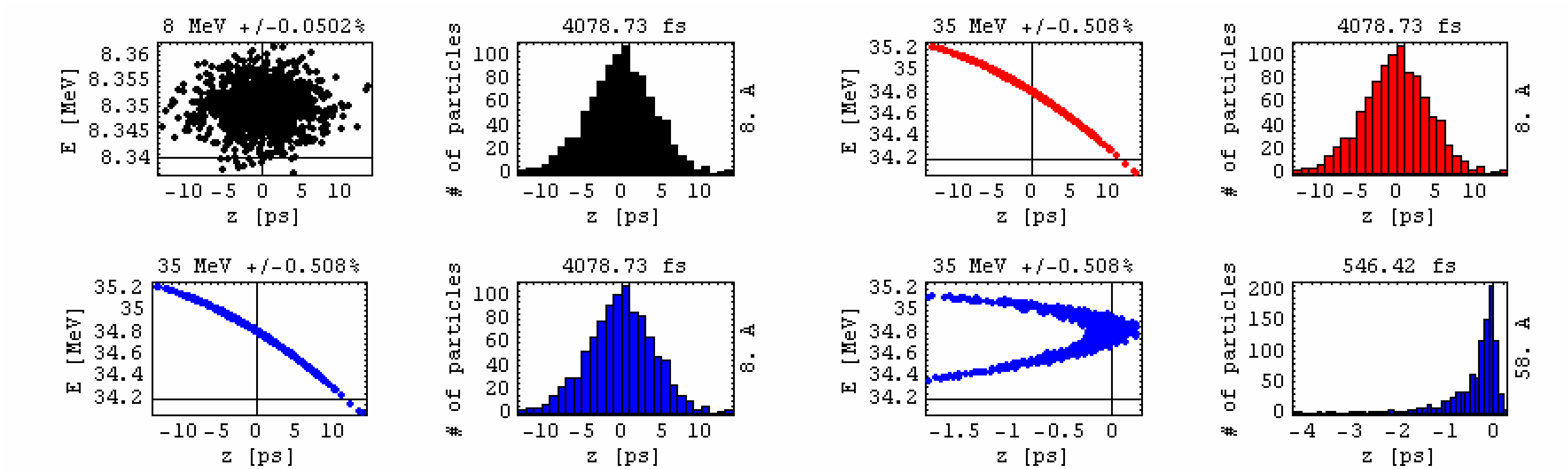
Main linac compression scheme



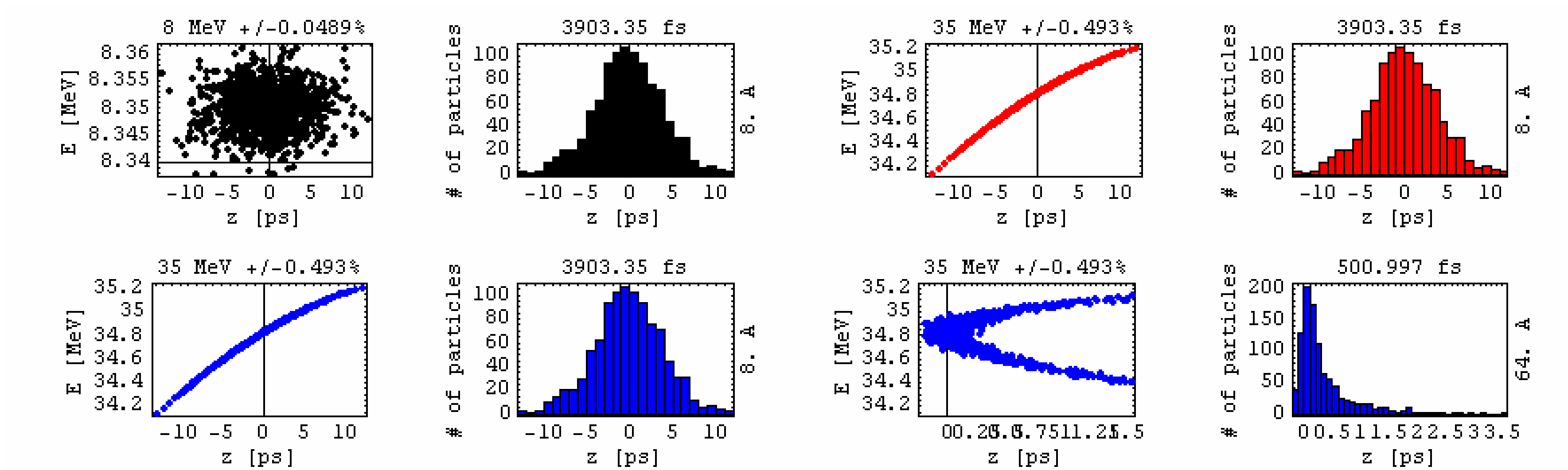


Longitudinal cavity wake from complete main linac
1 nC@40ps gives ~50 kV shift to 80 pC bunch (~10-4 at 600 MeV)

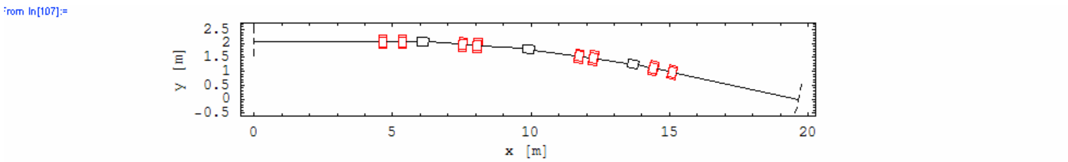
Signs of Compression

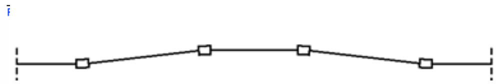


Only the phases and signs of compression are different



Polarity of R56 – A and B Type Compression

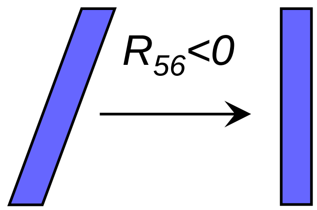


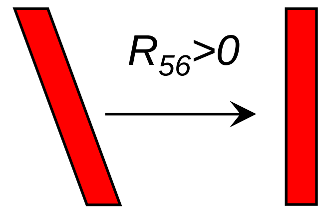


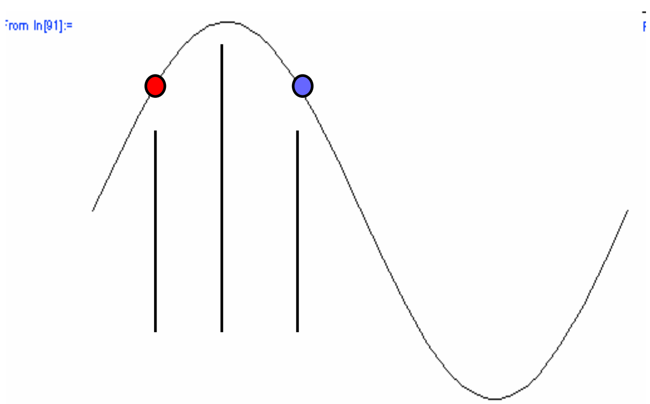
A – Arc-like

$$R_{56} = \int \frac{\eta(s)}{\rho(s)} ds$$

B – BC-like







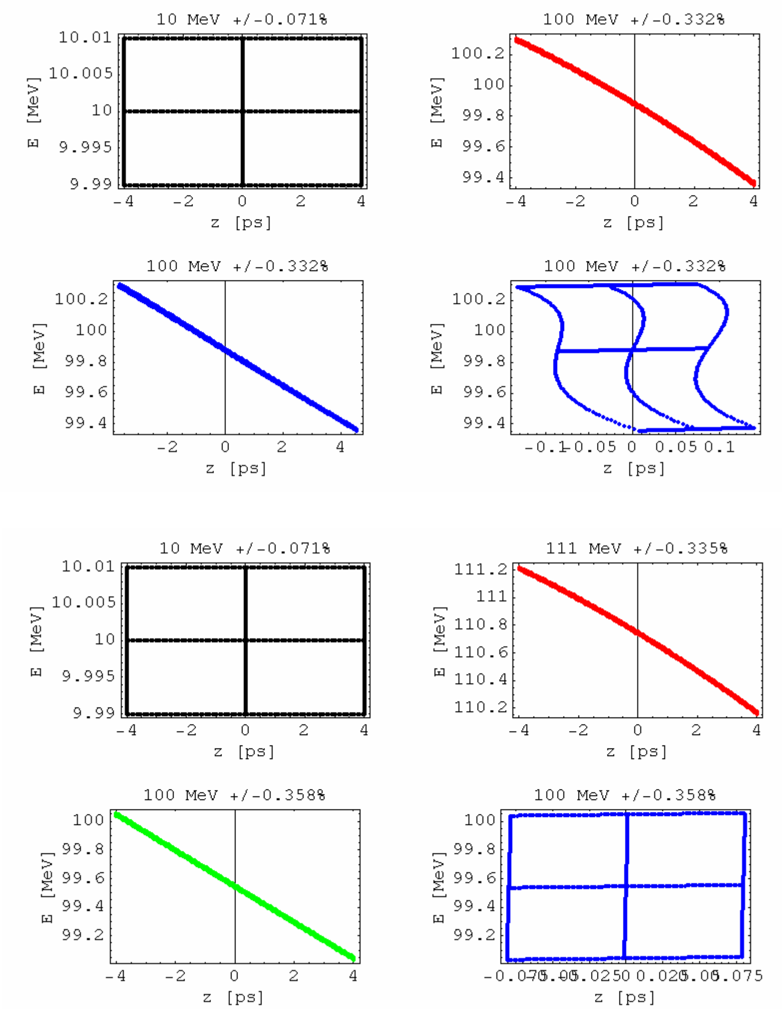
A chirp goes with A compression
B chirp goes with B compression

Your sign convention is up to you!

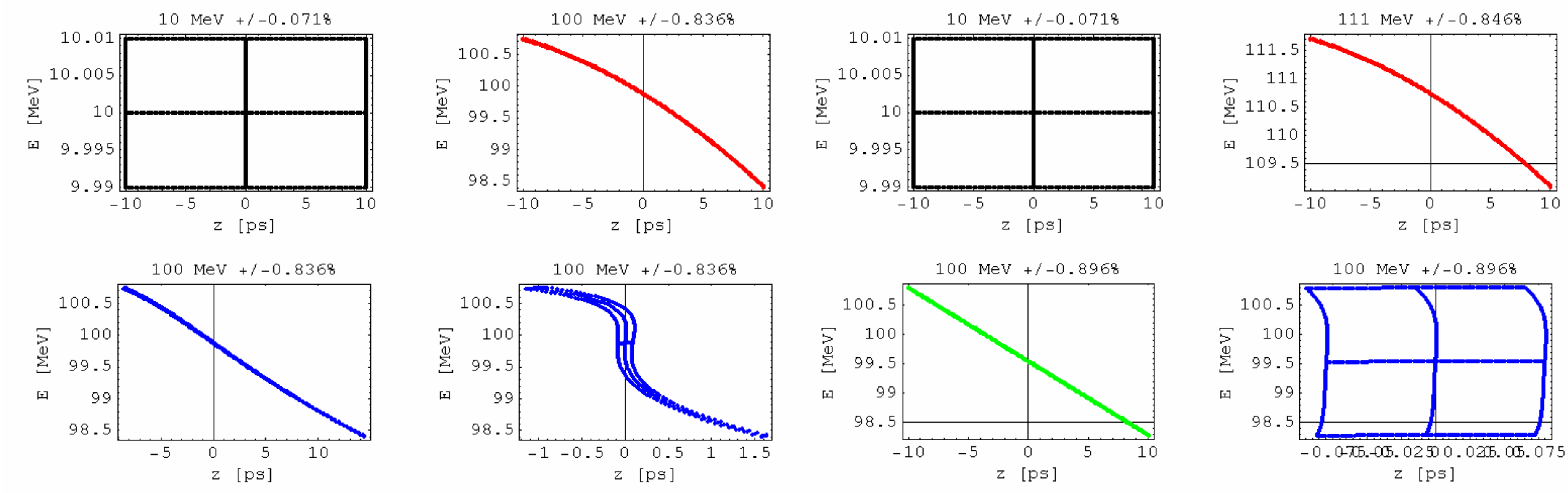
Wakefield and CSR Issues can help you choose which way round!

Higher-Harmonic or Sextupoles?

- At first glance, higher-harmonic and T566 correction look pretty equivalent
  - This is true unless you are *really* pushing your parameters
- Consider a toy system
  - 10 to 100 MeV
  - Single stage
  - T566 or 3rd harmonic
  - All parameters optimised
- *Third harmonic is more effective at linearising than T566*



What happens with a longer bunch length?



T566 (Sextupoles)

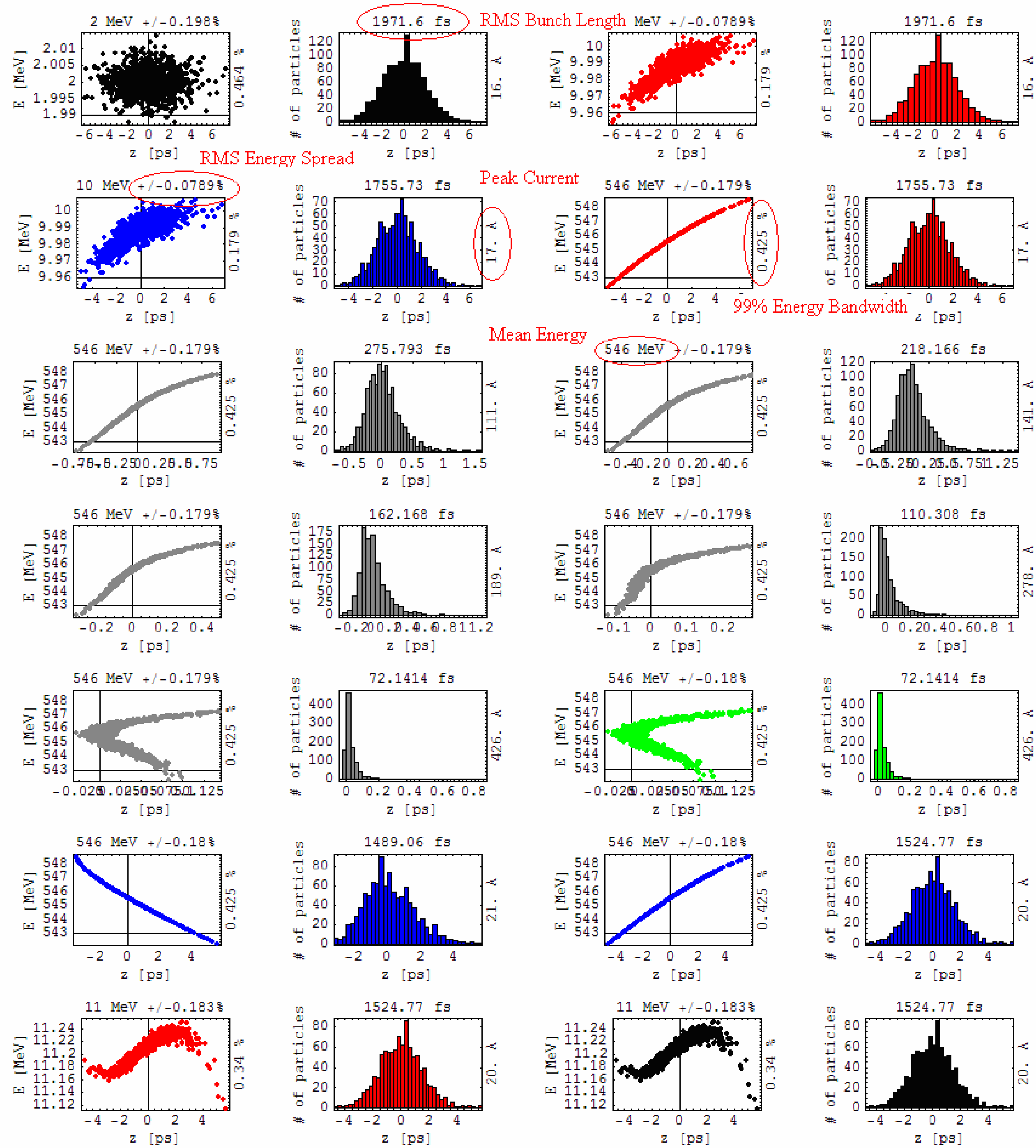
Third Harmonic
10x smaller bunch length!

- This behaviour is probably generally true
- If you want to use sextupoles, then you have to keep your input (injector) bunch length short
  - 4GLS HACL injector meets these requirements – about 2ps/0.4% at 10 MeV

HACL v1.1

- No lasing

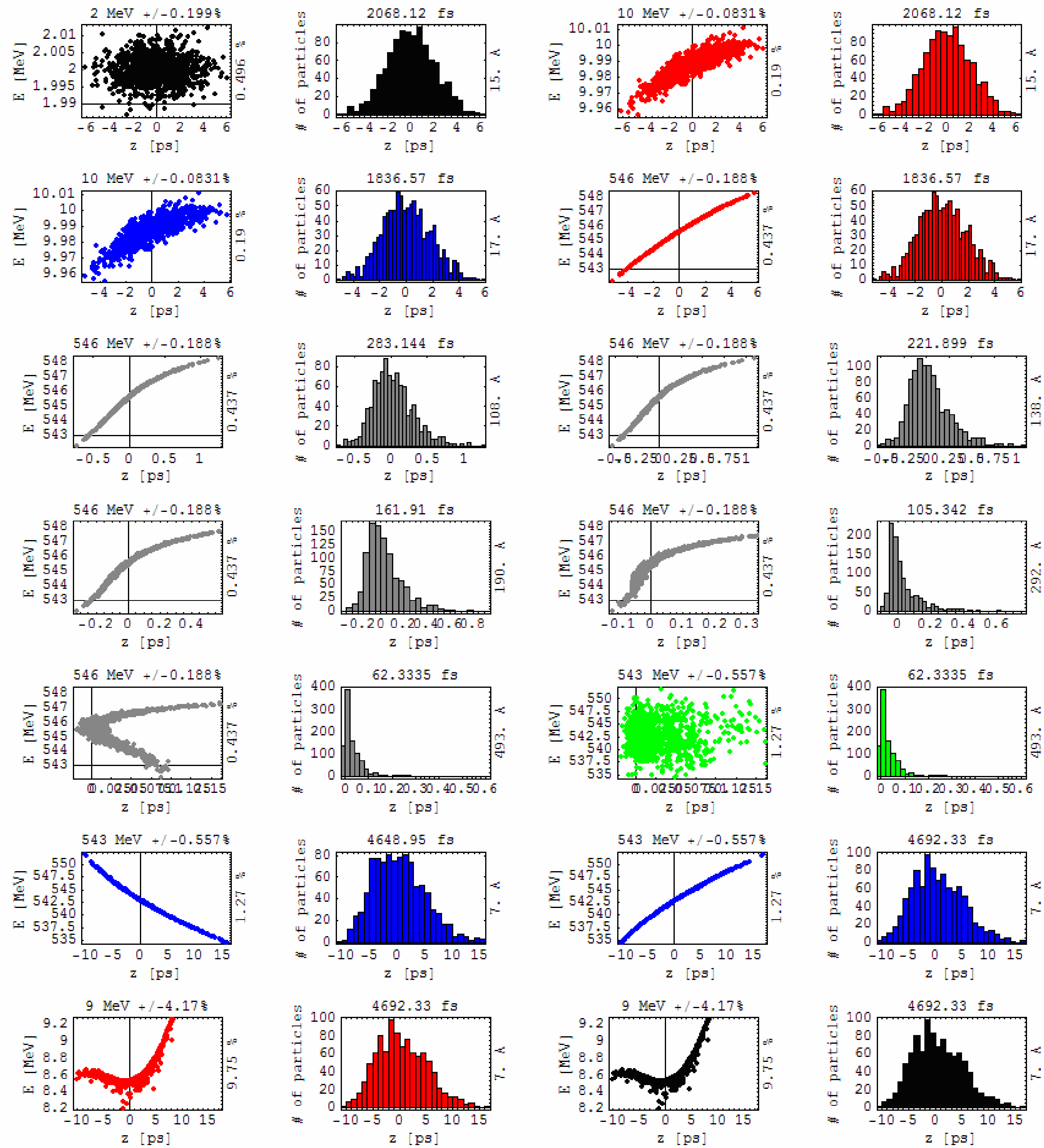
- (1D Model)



HACL v1.1

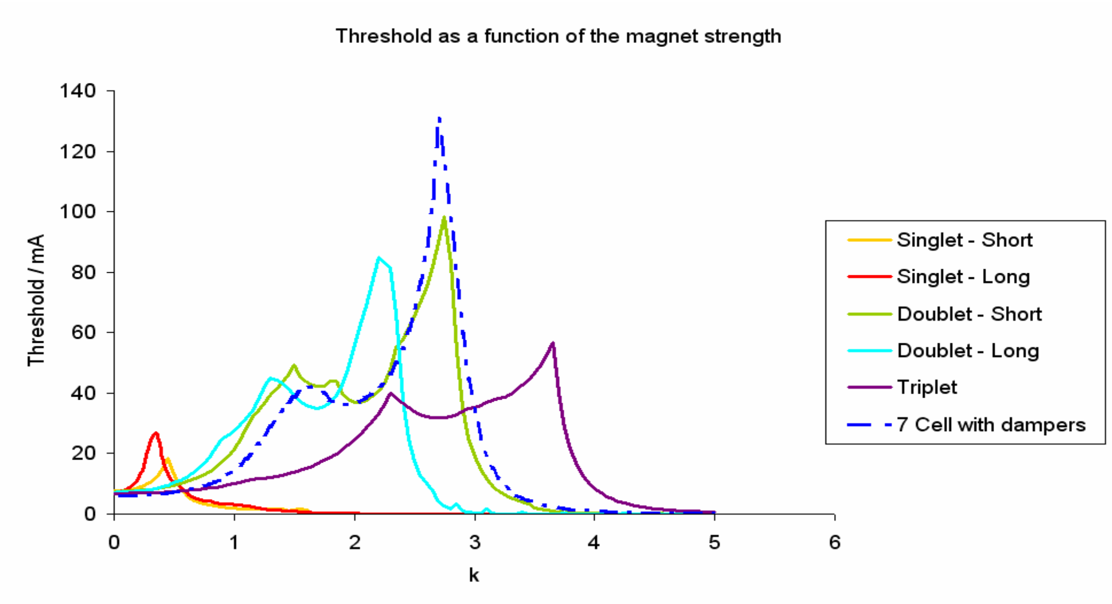
- Lasing

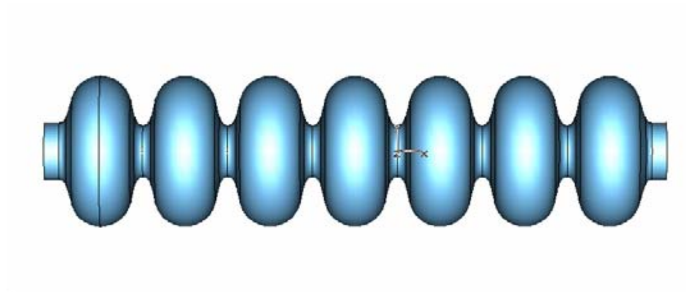
- (1D model)



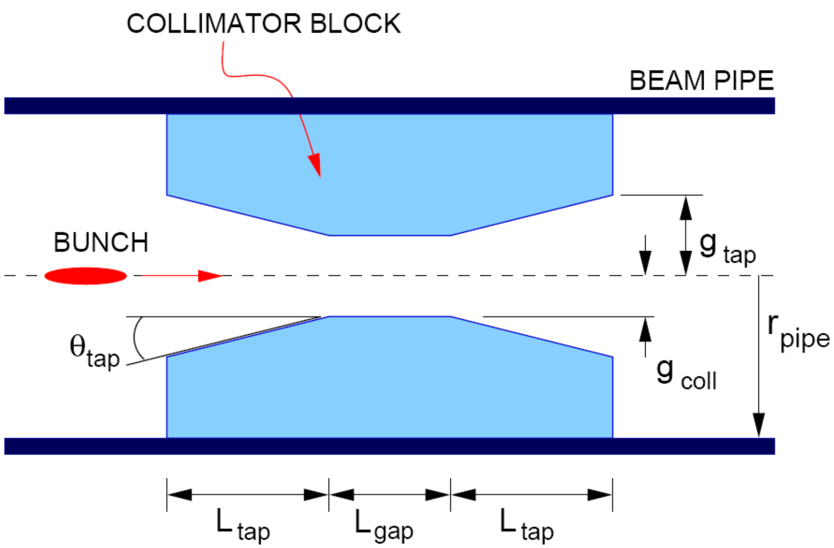
HACL BBU Threshold

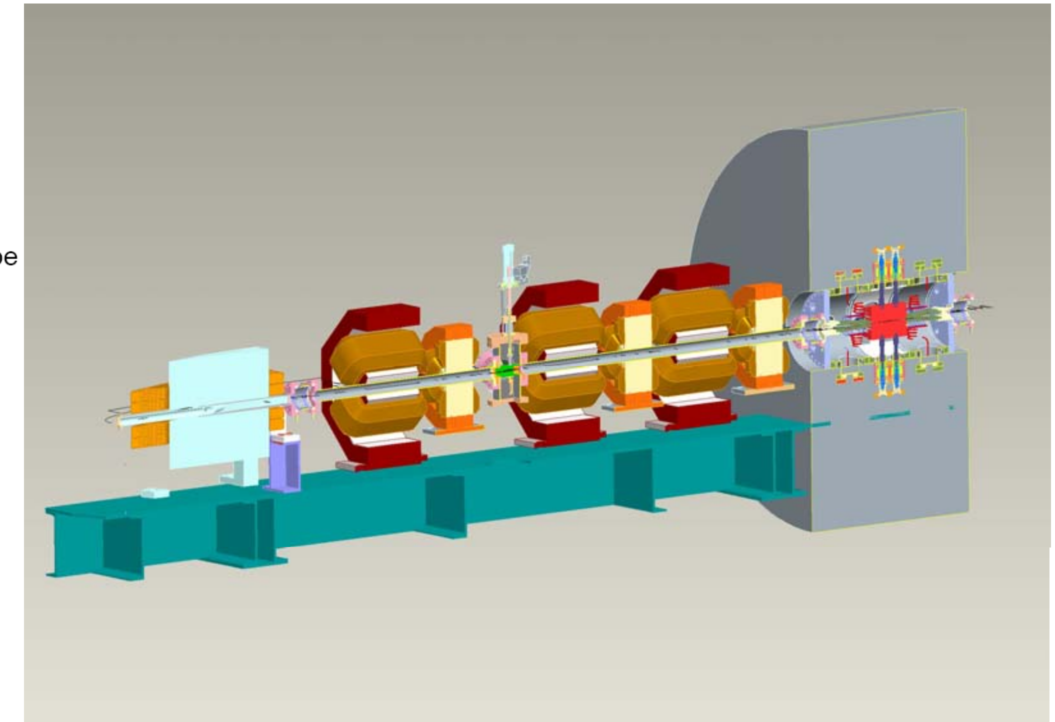
- 4GLS will use 7-cell cavities adapted from TESLA 9-CELL cavities
- These have been modelled in Microwave Studio
- For more accurate modelling the couplers and dampers must be included
- BBU threshold depends on HOMs and focusing scheme
  - Using doublet scheme similar to Cornell ERL (half-half)
- See more detailed talk by Emma Wooldridge

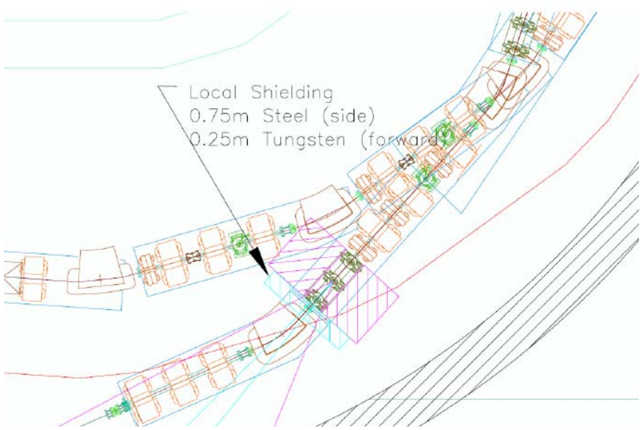




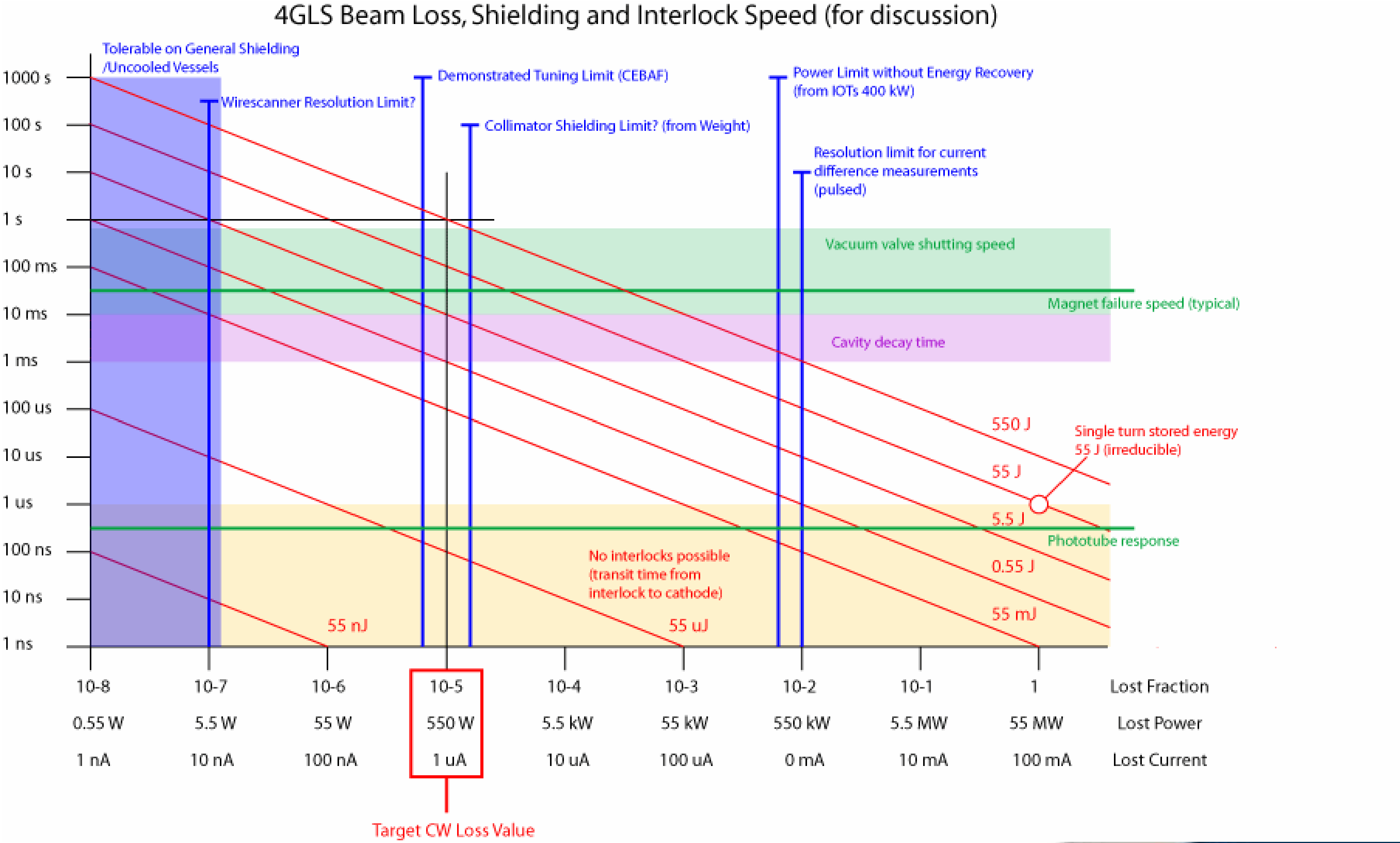
Collimation in 4GLS



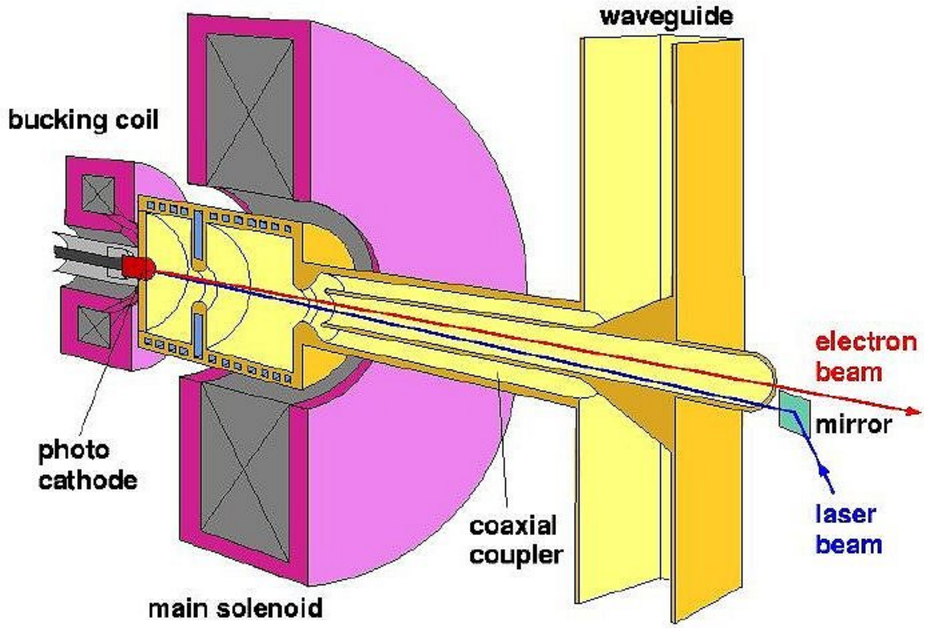


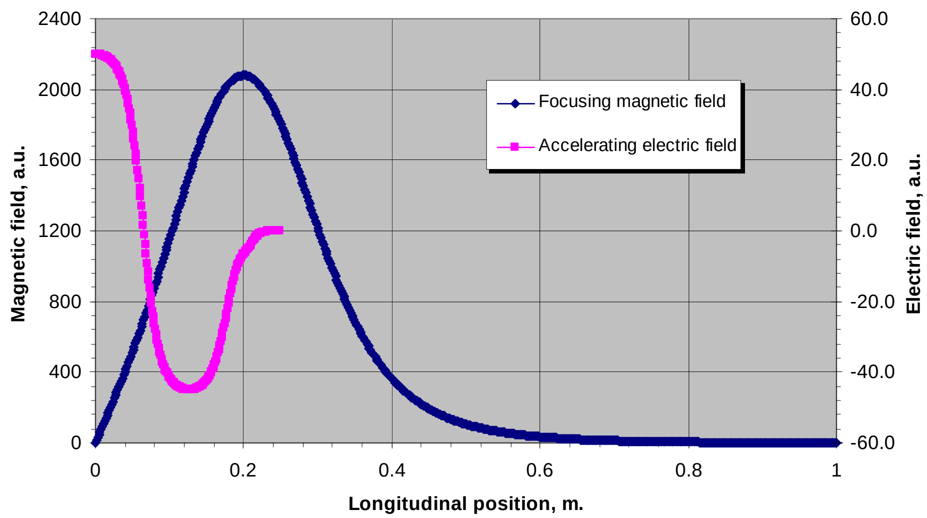


4GLS Shielding and Interlocks



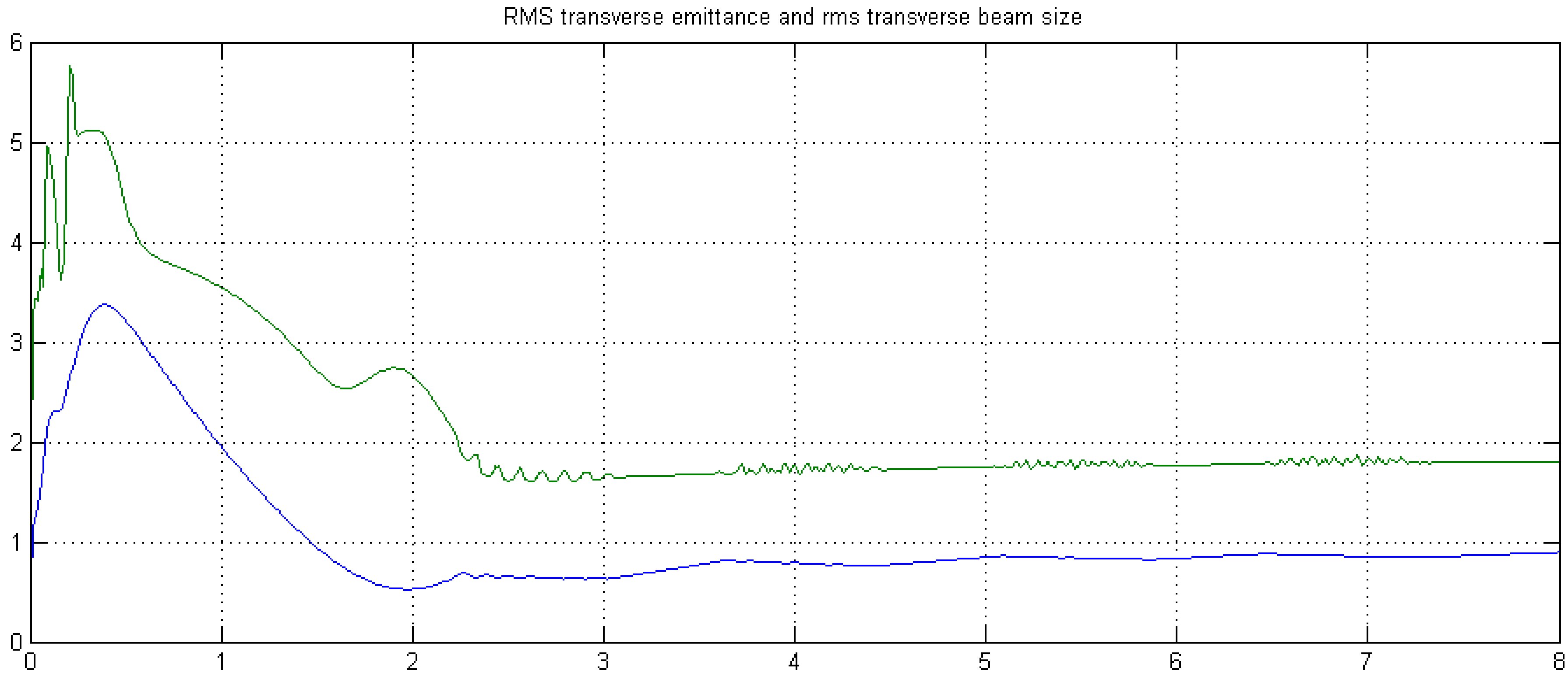
Normal conductive 1.5-cell RF photocathode gun



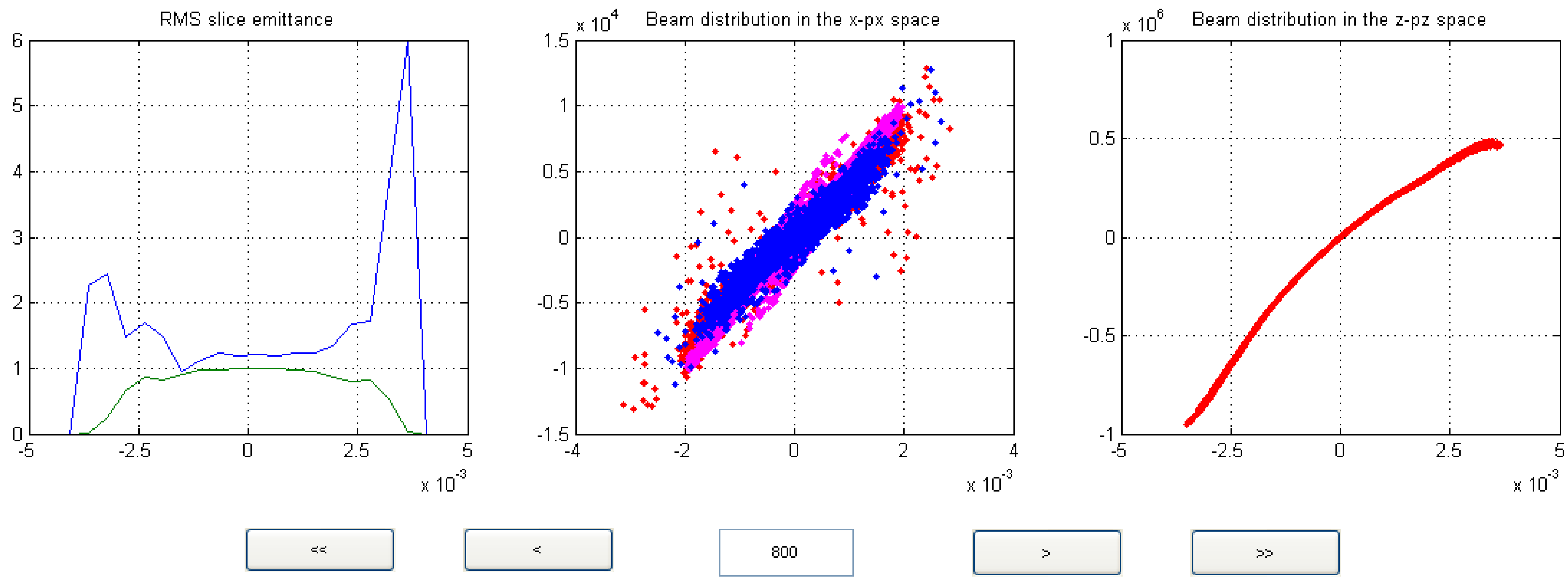


Distribution of accelerating RF and focusing magnetic field in the gun

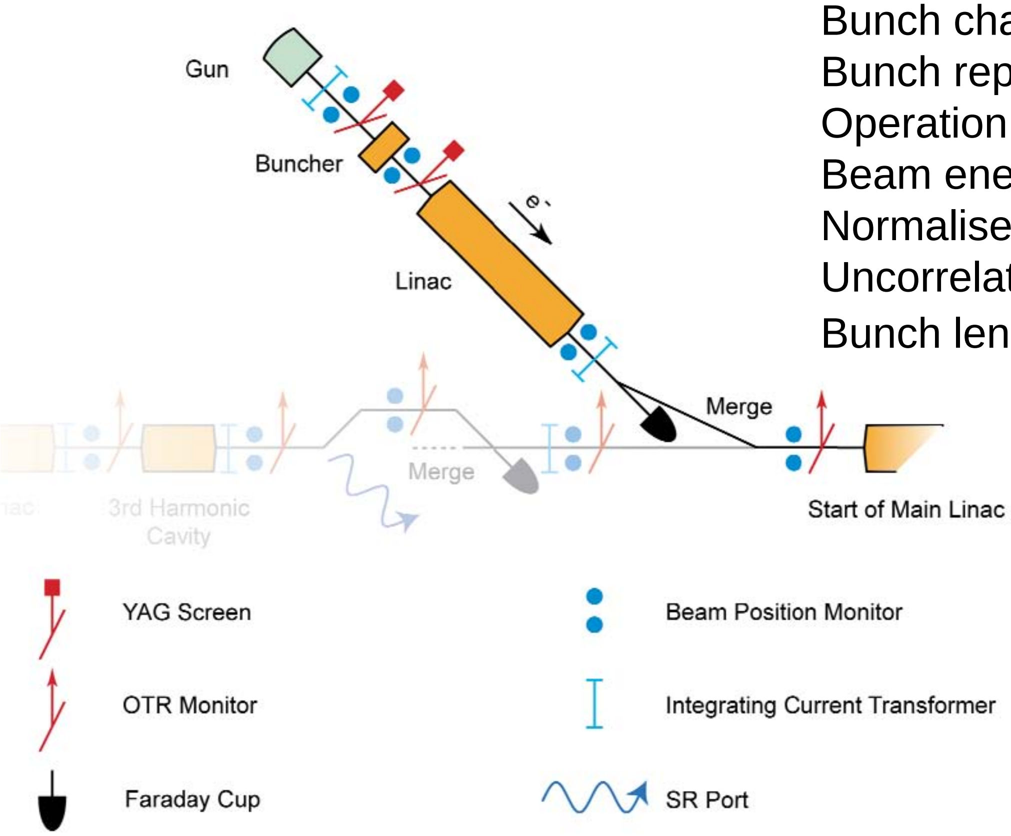
ASTRA simulation of the XUV-FEL injector



ASTRA simulation of the XUV-FEL injector



VUV-FEL injector



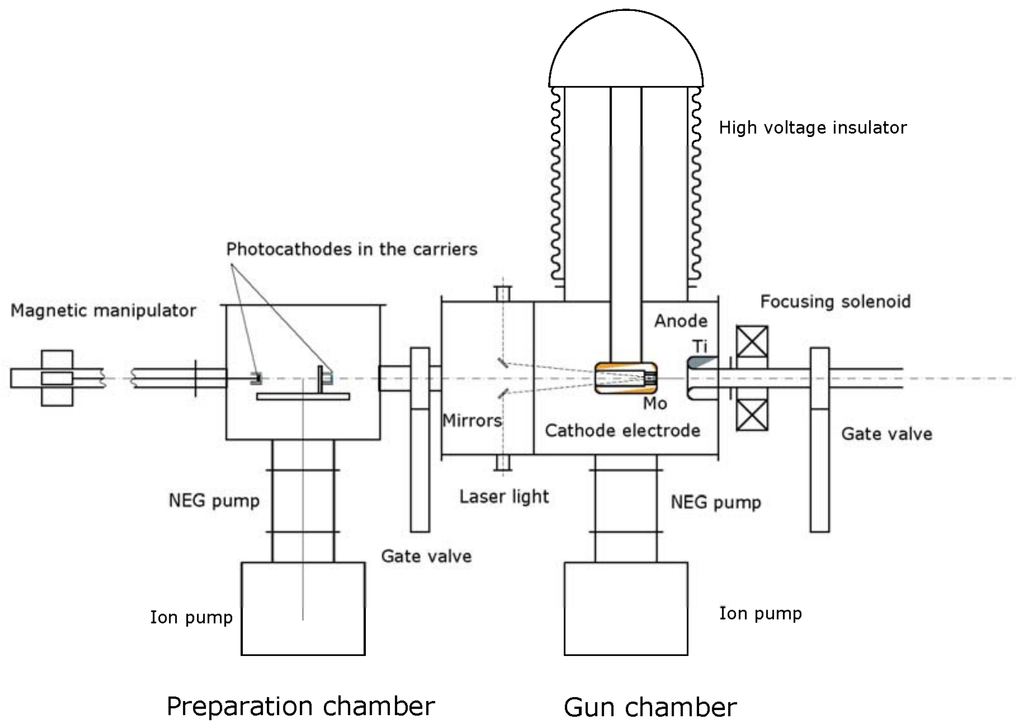
Beam parameters at the entrance of main linac

Bunch charge, pC	*77*
Bunch repetition rate, GHz	1.3
Operation mode	CW
Beam energy, MeV	10
Normalised beam emittance, π·mm·mrad	< 2
Uncorrelated energy spread, %	< 0.2
Bunch length, ps	2

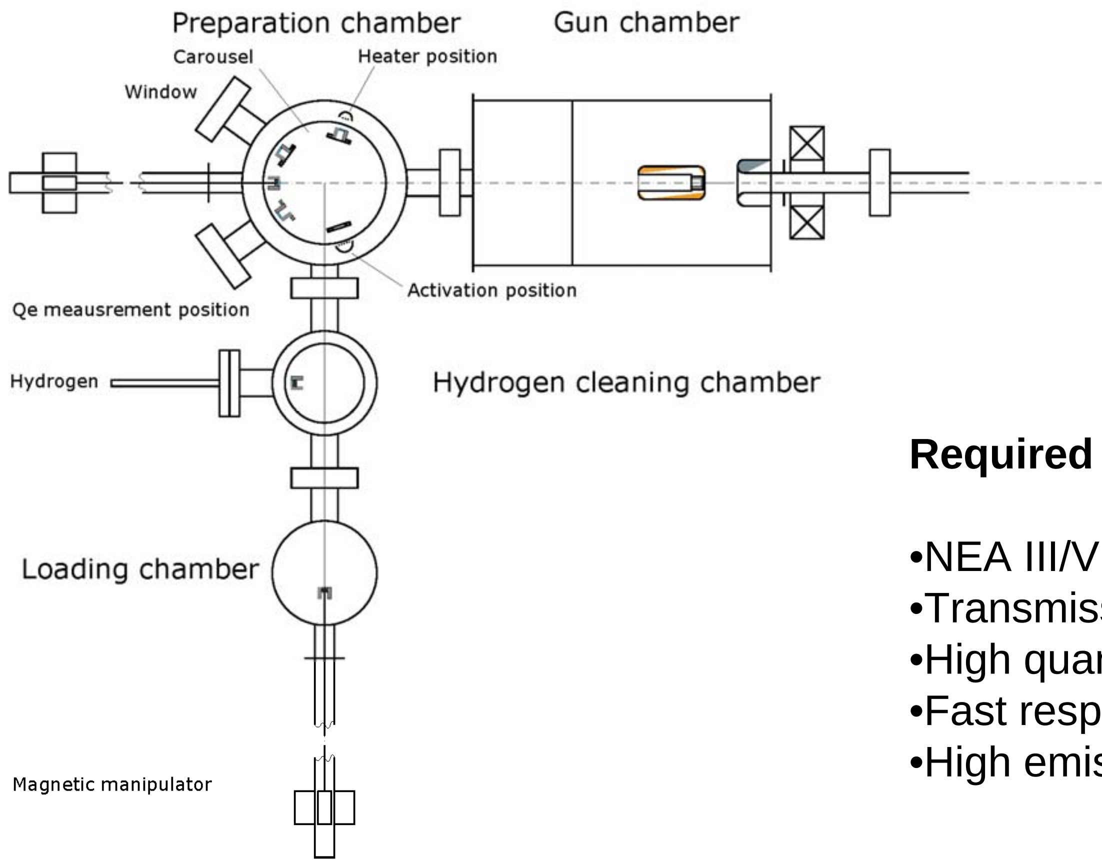
High voltage DC photocathode gun

Parameter of the photocathode gun

Gun voltage, kV	500
Average beam current, mA	100
Bunch repetition rate, GHz	1.3
RMS laser pulse length, ps	20
Laser pulse shape	Gaussian
Estimated operational life time, hours	27
Estimated rms transverse emittance, π·mm·mrad	2.8
Estimated rms bunch Length, ps	30



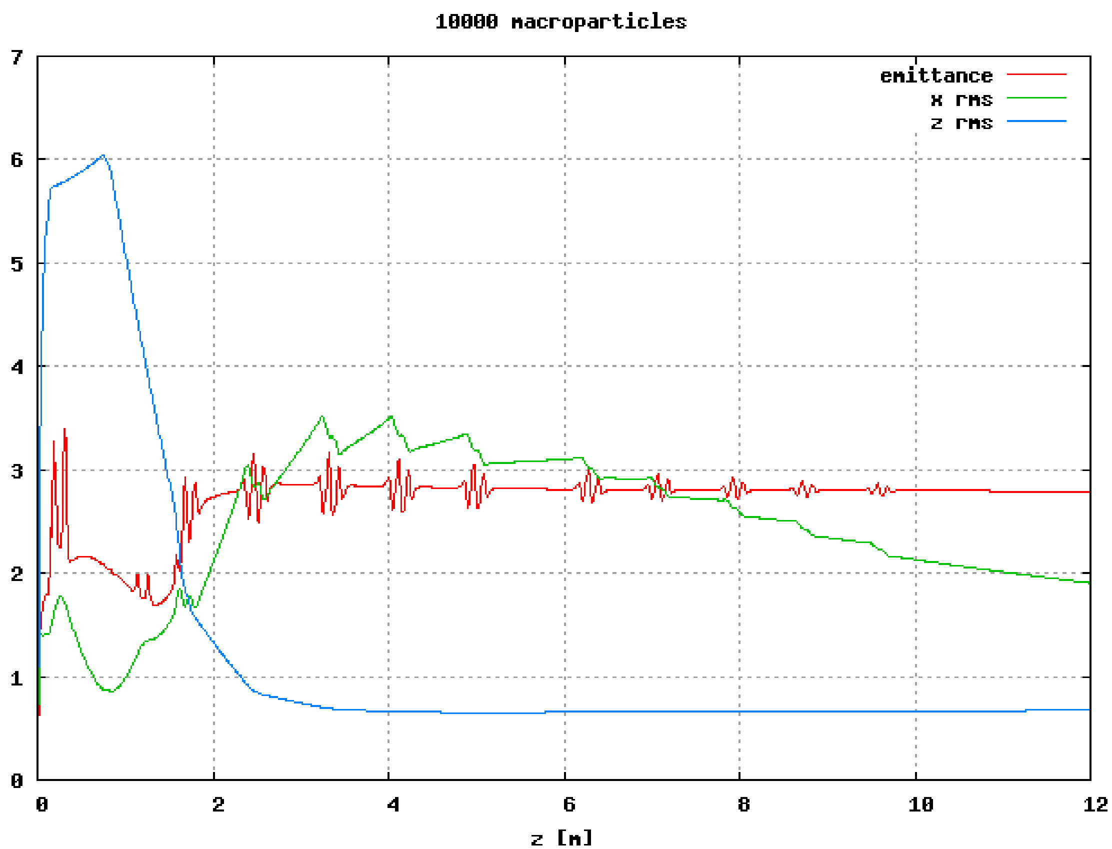
Photocathode preparation set-up

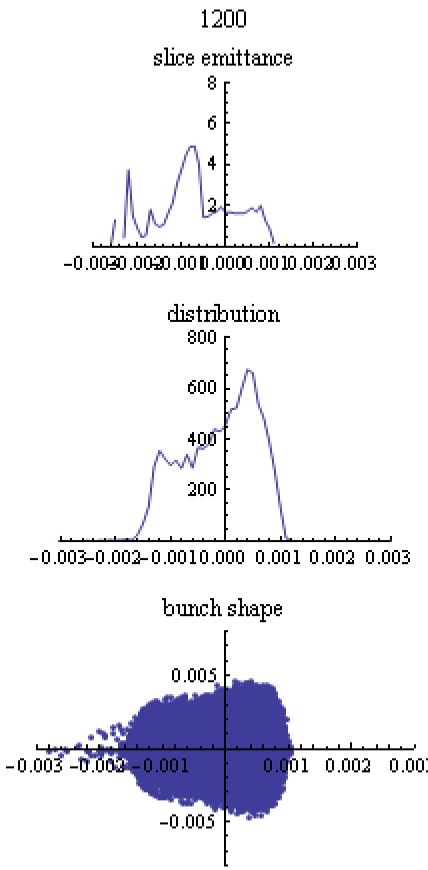


Required photocathodes:

- NEA III/V semiconductor
- Transmission mode
- High quantum efficiency
- Fast response
- High emission current density

Beam dynamics in the VUV-FEL injector





Laser for VUV-FEL injector

For GaAs photocathodes *λ<850 nm, for λ=520 nm*

Wavelength, nm	520
Repetition rate, GHz	1.3
RMS pulse with, ps	10
Average laser power for Q_e=10%, W	2.3
Average laser power for Q_e=1%, W	23
Average laser power for Q_e=1%,η=0.7, W	33
Timing jitter, fs	100

4GLS Timescales

✓ **April 02**	Scientific case approved (Gateway 0)
✓ **Nov 02**	Business case approved (Gateway 1)
✓ **April 03 & 04**	£13.9 M funding for prototype accelerator (ERLP) and R&D (OST £8 M, CCLRC £5.9 M)
✓ **Feb 05**	EUROFEL R&D work funded (Euro 9M)
✓ **March 05**	Funding for 4GLS Technical Design (CCLRC £1.6 M)
✓ **Nov 05**	£3 M NWSF funding for ERLP science
✓ **Spring 06**	4GLS CDR

- **summer 2007** Review of light source provision for UK
- **late 2007** ERLP energy recovery
- **spring 2008** 4GLS TDR
- **2008/09/10** Approval for 4GLS and first spend
- **2013/14** Facility starts to become available to researchers

Other Things…

- Things I haven't mentioned:
  - Path Length Correction
  - Jitter and lasing tolerances (N. Thompson, G. Hirst etc. etc.)
  - XUV-FEL – S2E by Peter Williams
  - High power dump – Novosibirsk/RAL

- Thanks to:
  - 4GLS staff
  - Collaborators, including:
    - JLab
    - EuroFEL
    - Cornell
    - Stanford
    - Novosibirsk
    - MaxLab
  - Everyone else who's helped us
    - Esp. discussions at this workshop and the last one

www.4gls.ac.uk

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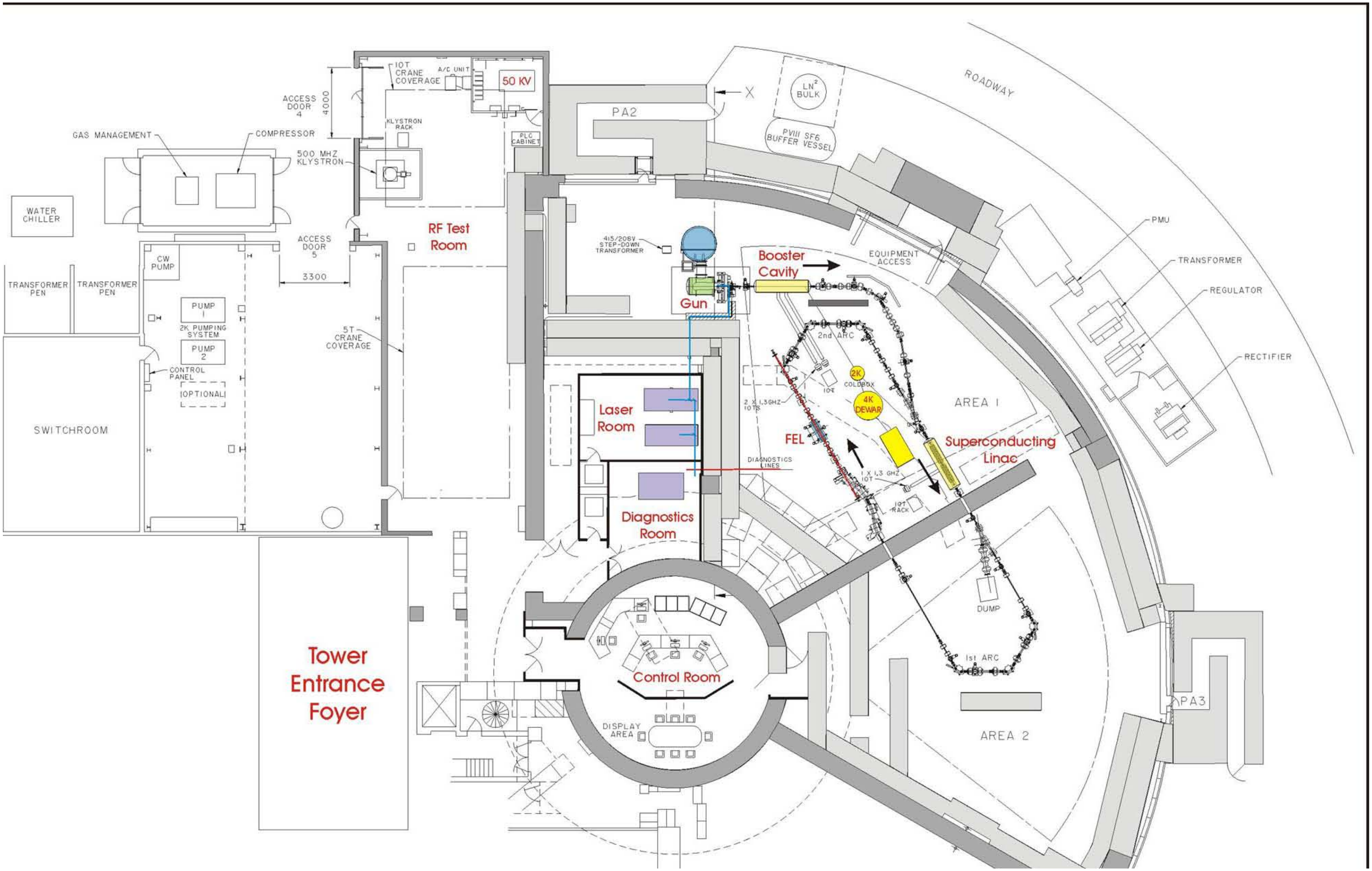
ERLP Status

- Introduction
- Laser, gun
- Diagnostic line
- Injector commissioning
- Cryogenics
- Superconducting RF
- Beam transport system
- Ongoing work
- Future plans

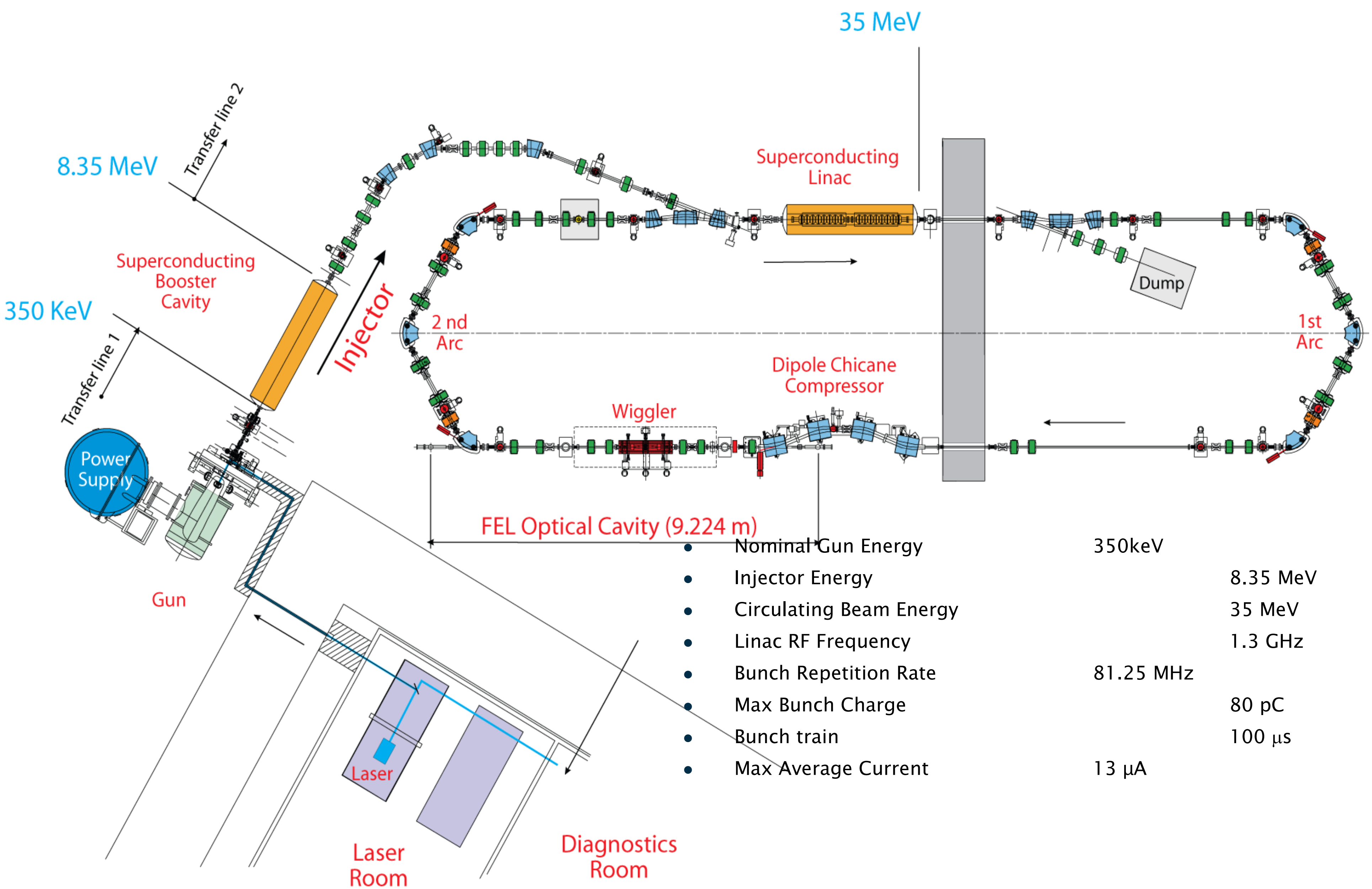
Technical Priorities for the ERL Prototype

- Operate a superconducting linac
- Produce and maintain bright electron bunches from a photoinjector
- Produce short electron bunches from a compressor
- **Demonstrate energy recovery**
- Demonstrate energy recovery (with an insertion device that significantly disrupts the electron beam)
- Have an FEL activity that is suitable for the synchronisation needs
- Produce simultaneous photon pulses from a laser and a photon source of the ERL Prototype that are synchronised at or below the 1ps level



RF Test Room
50 KV
10T CRANE COVERAGE
A/C UNIT
ACCESS DOOR 4
4000
KLYSTRON RACK
PLC CABINET
GAS MANAGEMENT
COMPRESSOR
500 MHZ KLYSTRON
WATER CHILLER
ACCESS DOOR 5
3300
CW PUMP
TRANSFORMER PEN
TRANSFORMER PEN
PUMP 1
2K PUMPING SYSTEM
PUMP 2
CONTROL PANEL
(OPTIONAL)
5T CRANE COVERAGE
SWITCHROOM
PA2
LN2 BULK
PVIII SF6 BUFFER VESSEL
ROADWAY
415/208V STEP-DOWN TRANSFORMER
Booster Cavity
Gun
EQUIPMENT ACCESS
2nd ARC
2K COLDBOX
4K DEWAR
2 X 1.3GHZ IOTS
AREA 1
FEL
Superconducting Linac
DIAGNOSTICS LINES
1 X 1.3 GHZ IOT
IOT RACK
Laser Room
Diagnostics Room
PMU
TRANSFORMER
REGULATOR
RECTIFIER
DUMP
1st ARC
AREA 2
PA3
Control Room
DISPLAY AREA
Tower Entrance Foyer

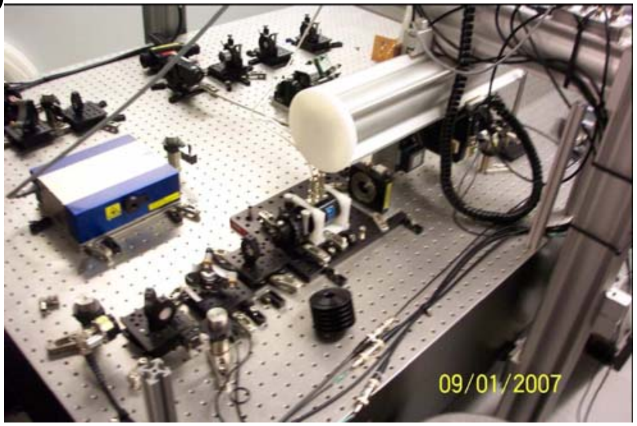
Accelerator Layout



- Nominal Gun Energy 350keV
- Injector Energy 8.35 MeV
- Circulating Beam Energy 35 MeV
- Linac RF Frequency 1.3 GHz
- Bunch Repetition Rate 81.25 MHz
- Max Bunch Charge 80 pC
- Bunch train 100 µs
- Max Average Current 13 µA

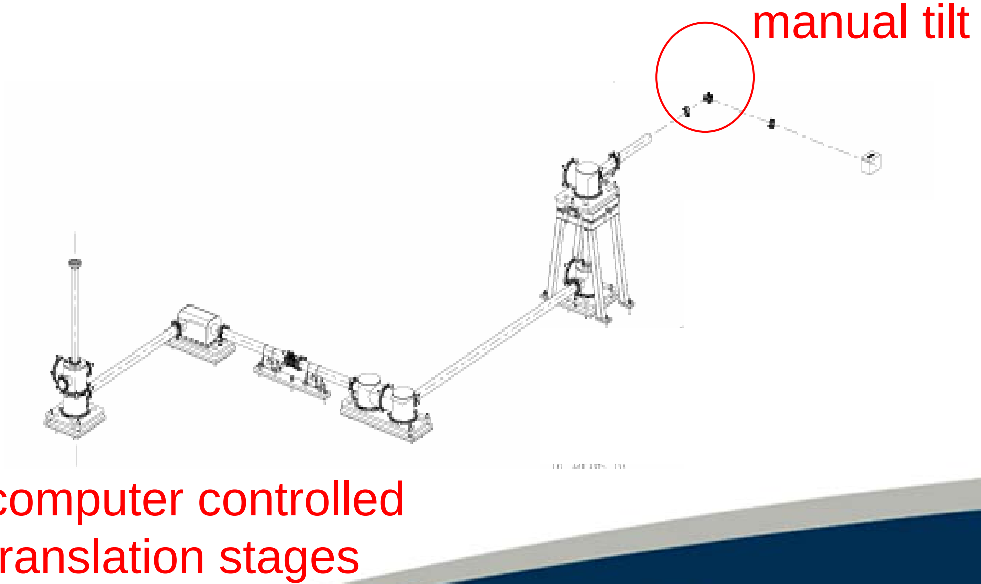
Laser

- Wavelength: 1.05μm, multiplied to 0.53μm/0.26μm (NdYvanadate)
- Pulse energy: 80nJ on target
- Pulse duration: 10ps FWHM
- Pulse repetition rate: 81 MHz
- Macropulse duration: 20 ms
- Duty cycle: 0.2%
- Timing jitter: <1ps
- Spatial profile: circular.top hat) on photocathode



✓ Laser system commissioned '05

✓ Laser & transport commissioned April '06



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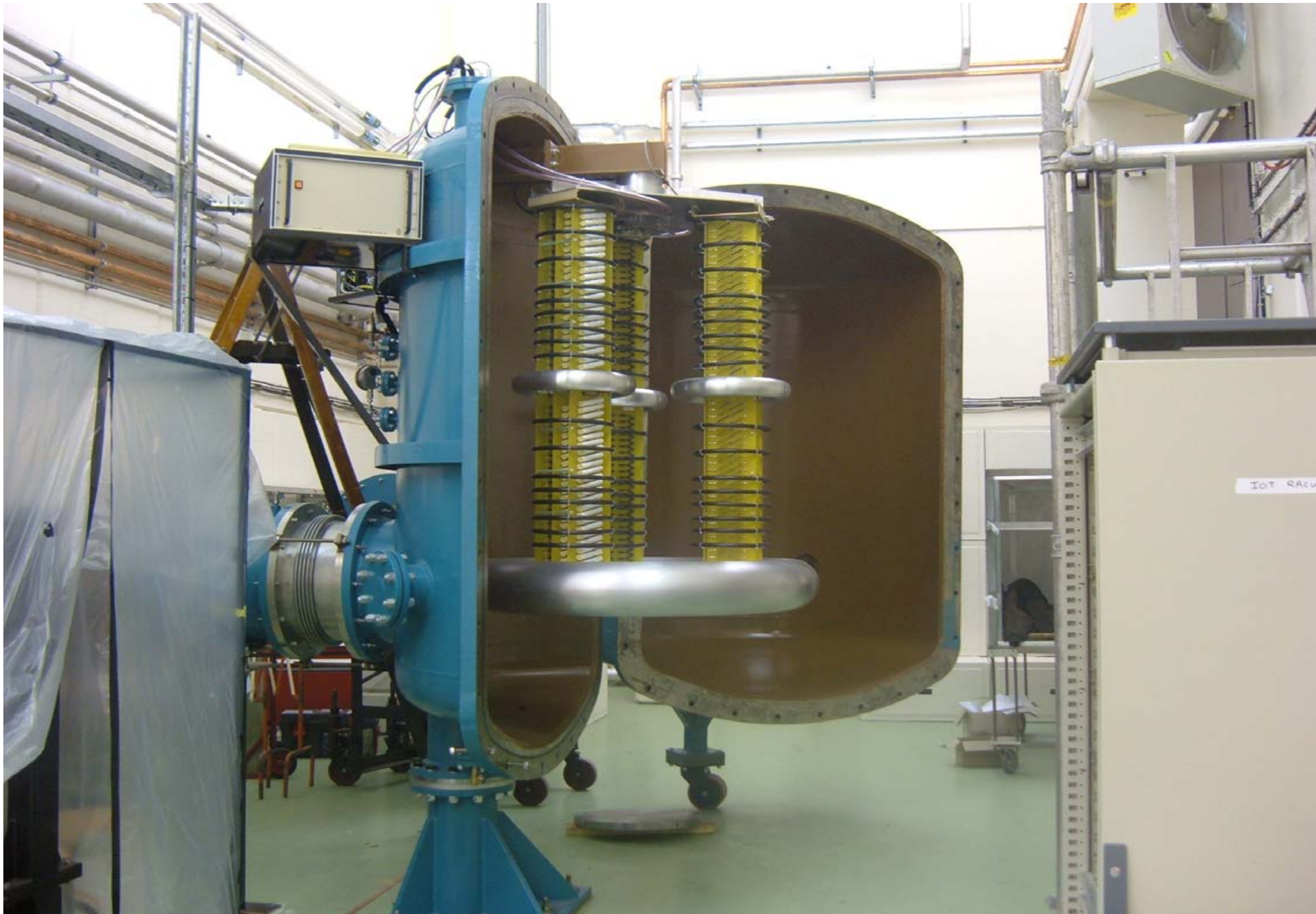
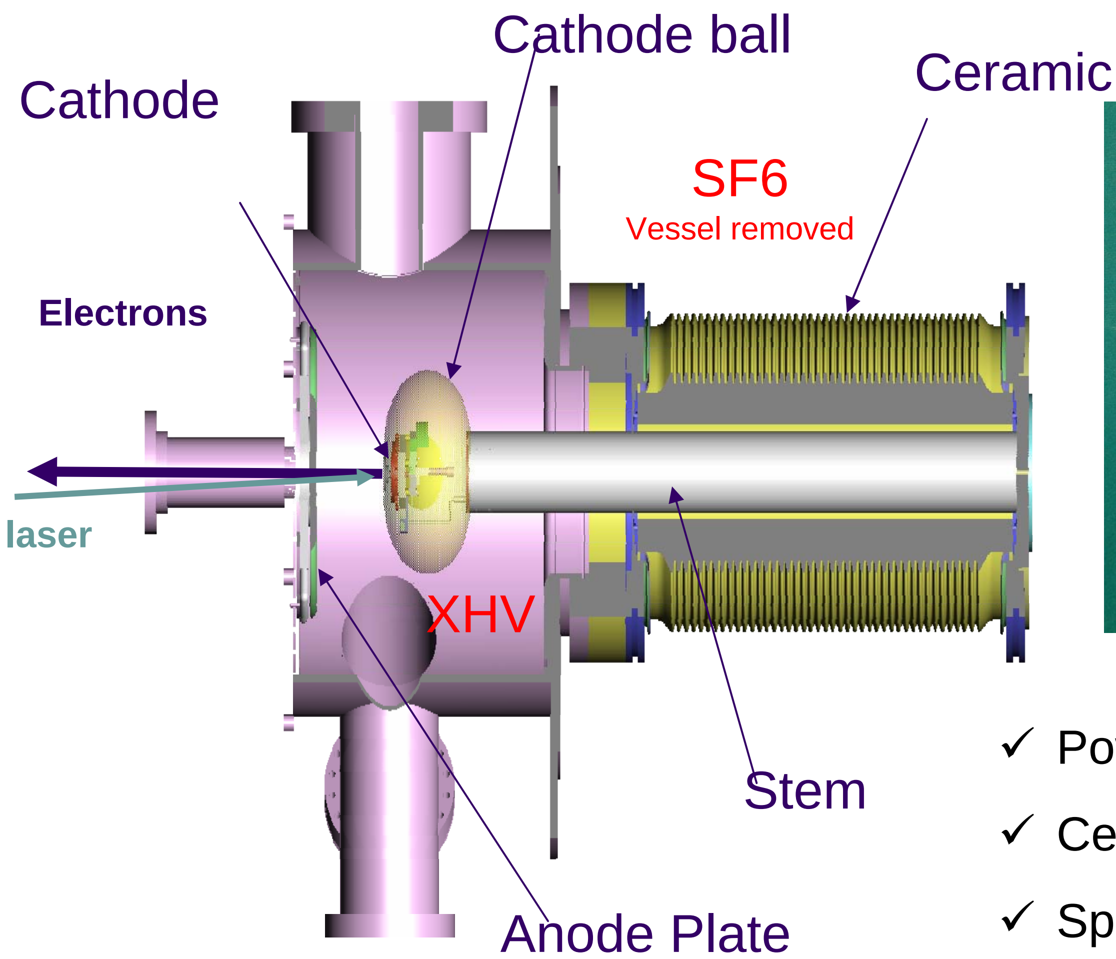
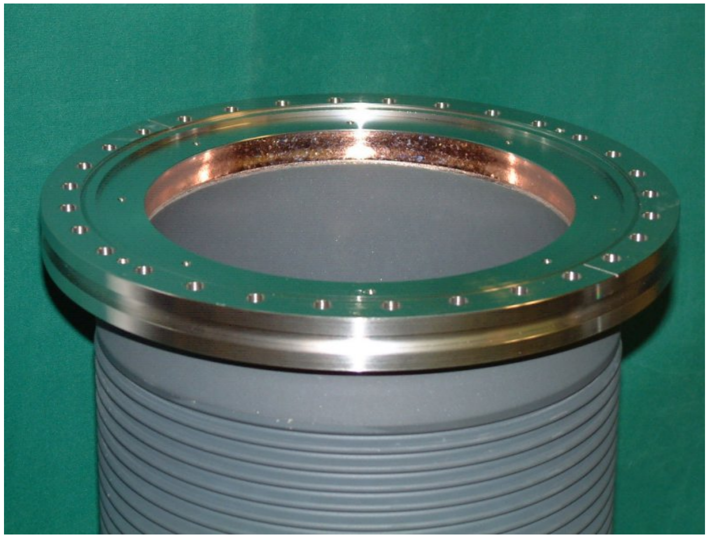
Gun Power Supply



Gun Assembly

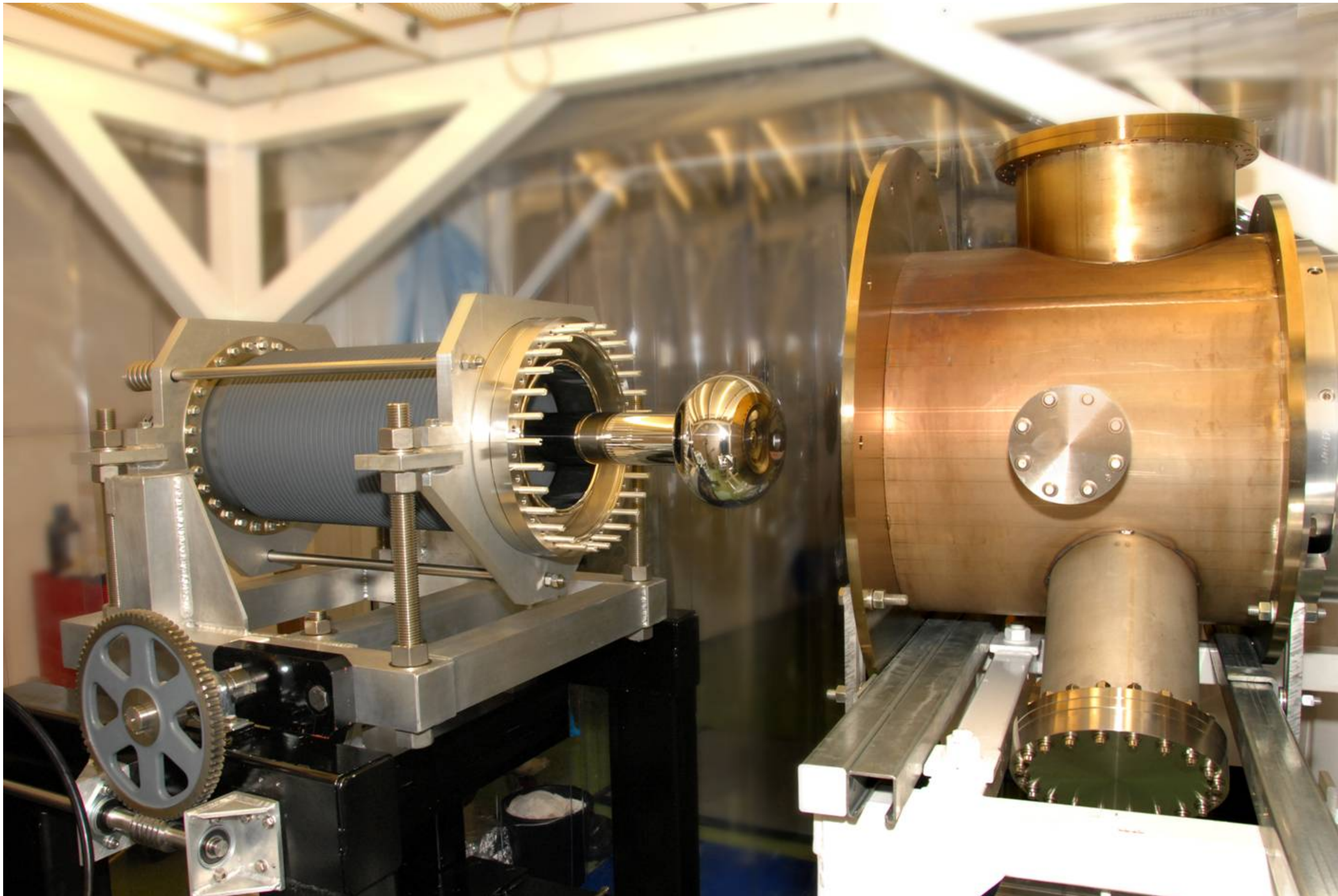
- JLab design GaAs cathode
- 500 kV DC supply
- transverse emittance ~3 mm mrad



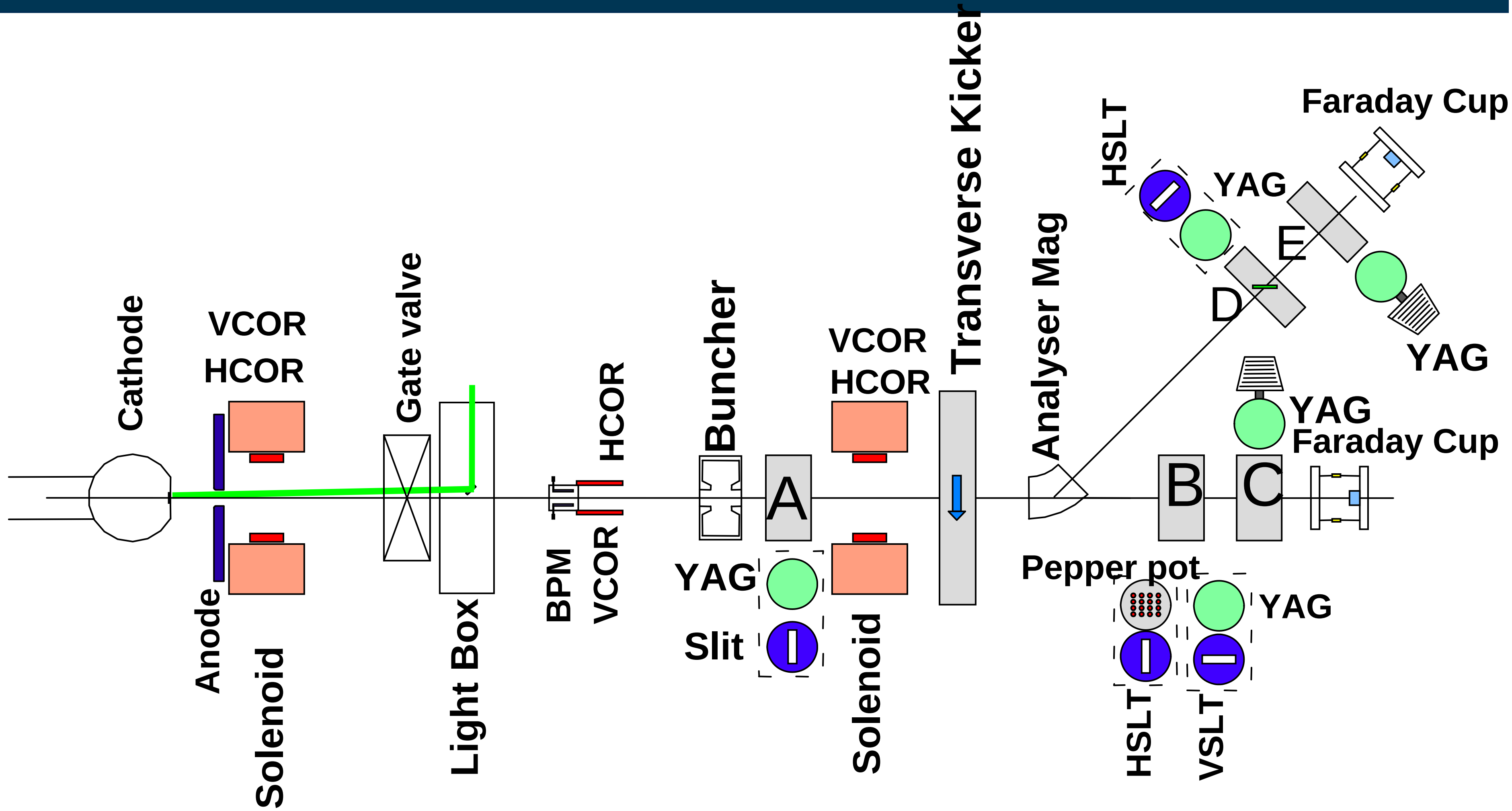


- ✓ Power supply commissioned ’05
- ✓ Ceramic delivery March ’06
- ✓ Spare ceramic delivered Nov ‘06

Ceramic, Cathode Ball and Gun



Diagnostics Line



Sections schematics when looking downstream (i.e. from the gun)

Gun Commissioning Status

- First beam at 01:08 on 16th August @ 250 kV
- Encouraging results obtained
- Contamination during cathode activation
- Limited by field emission to lower volts
- Cathode change after mechanical damage to flap
- Operation at 350 kV and 250 kV
- Diagnostic, buncher and kicker commissioned
- Cathode lifetime very poor, halo problems some field emission from flap during conditioning
- Change cathode, “solved” DC ion current problem, tightened handling methods, changed vacuum criteria, increased uniformity of bake, changed to NF_3
- Gun is currently under vacuum awaiting imminent delivery of high temp gaskets

First Beam!

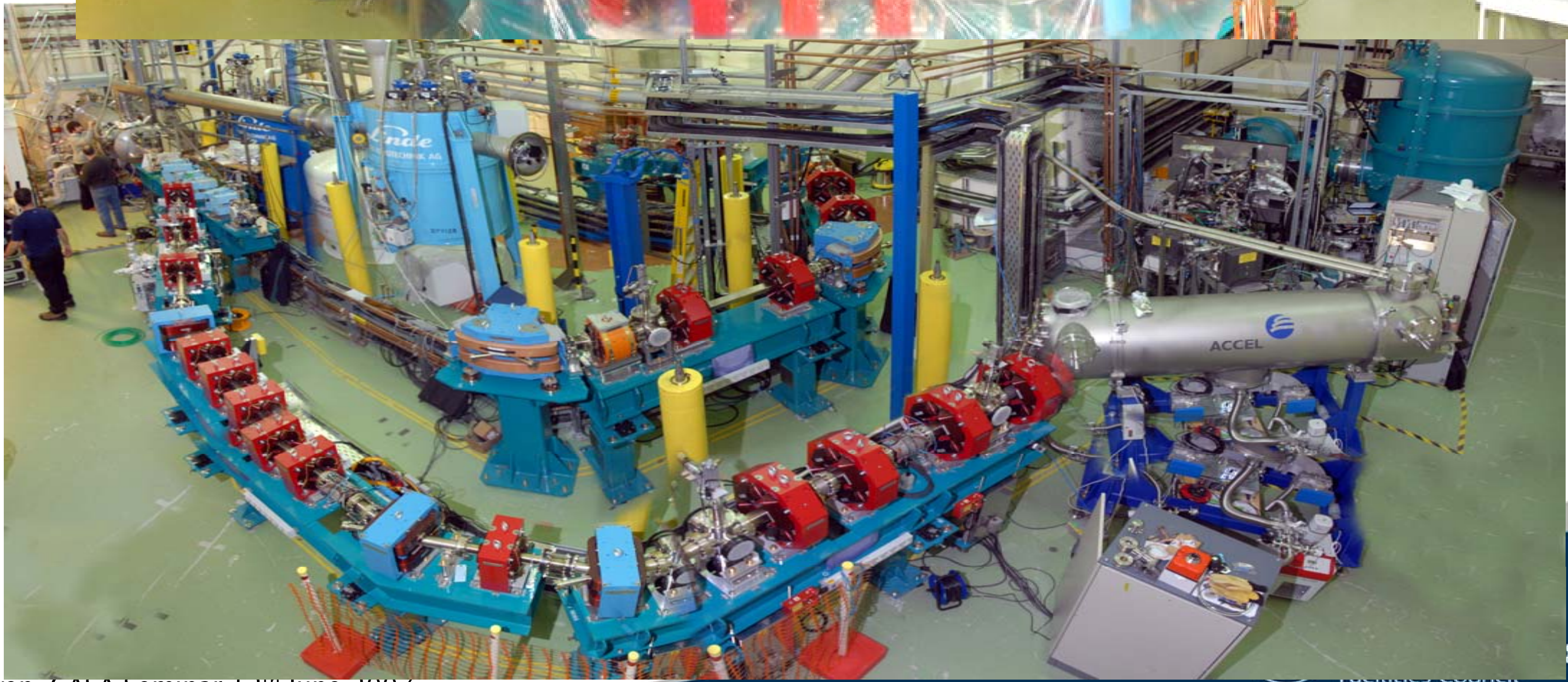
Performance Achieved So Far

- Beam energy 350 kV (spec value)
- Bunch charge 11 pC (22 pC) (ultimate target 80 pC)
- Quantum efficiency measured in the gun 1.2%, measured in the lab 3.5% (ultimate target ~few percent)
- Bunch train length 100 µs (spec value)
- Train repetition rate 20 Hz (spec value)

Cryosystem

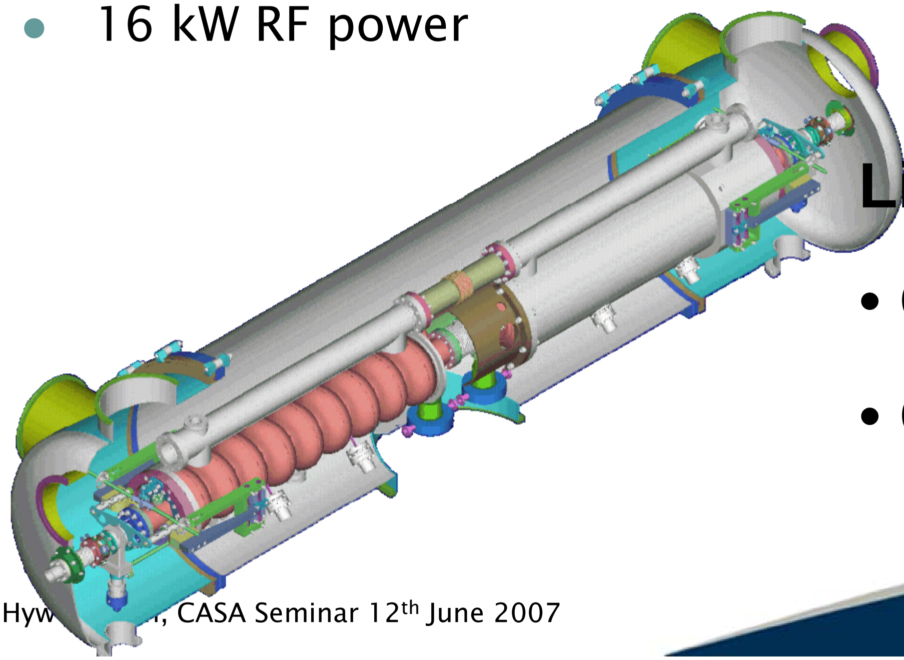
- 4 K commissioning was carried out May 06
- Module delivery April and July 06
- 2K cryogenic commissioning started Sept 06
- Both modules have been cooled to 2K early 07
- RF low level RF test confirmed booster HOM coupler OK.
- Problems transfer path heat leaks and heater failure
- **System Acceptance May 07**
- Will need to get many hours of operation under our belt before we have fully mastered cryosystem.

Cryosystem



Superconducting Modules

- 2 x Stanford/Rossendorf cryomodules – 1 Booster and 1 Main LINAC.
- Booster module:
  - 4 MV/m gradient
  - 32 kW RF power
- Main LINAC module:
  - 14 MV/m gradient
  - 16 kW RF power



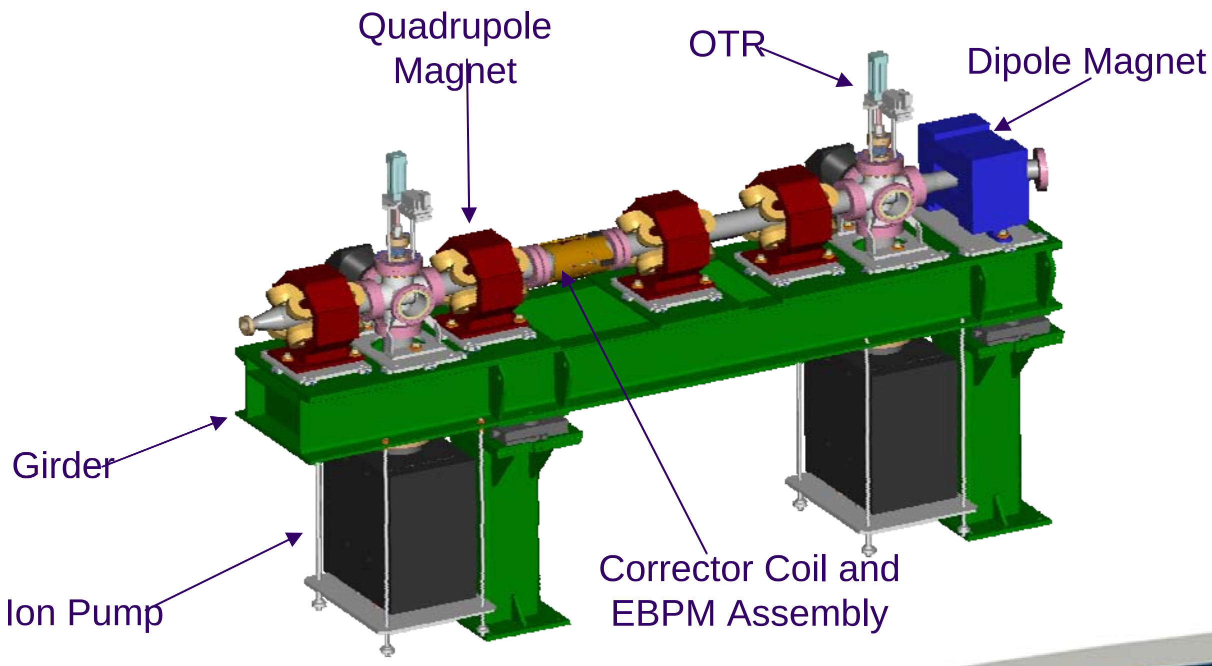
Delivery April/July 2006

Linac high power tests now.

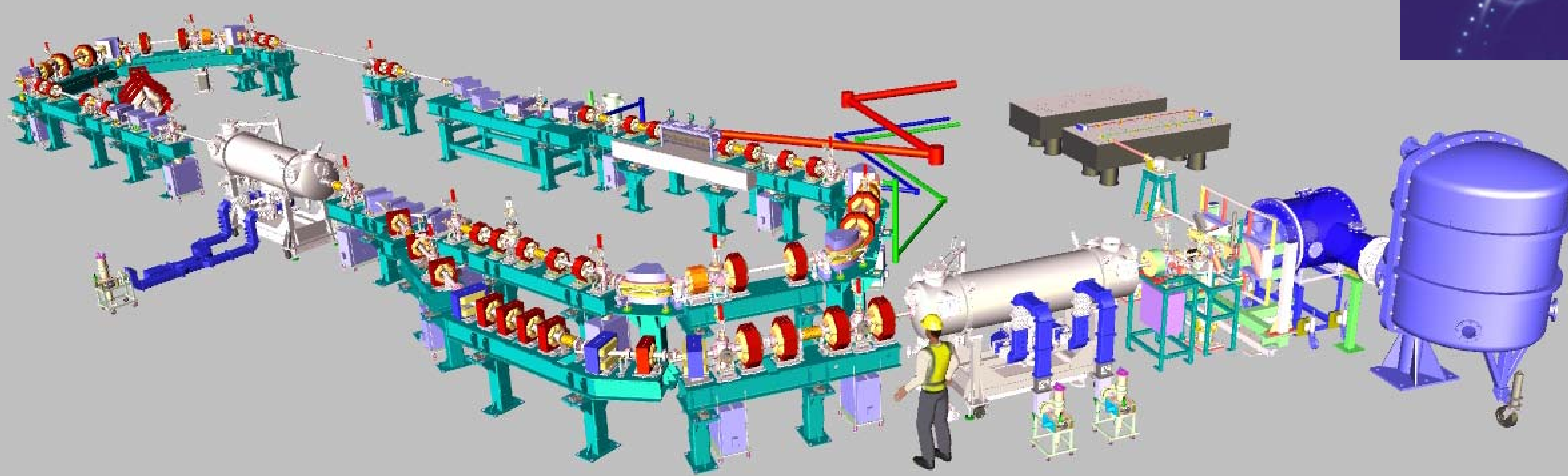
- Cavity 1 :13 MV/m
- Cavity 2 :10 MV/m

Electron Beam Transport System Status

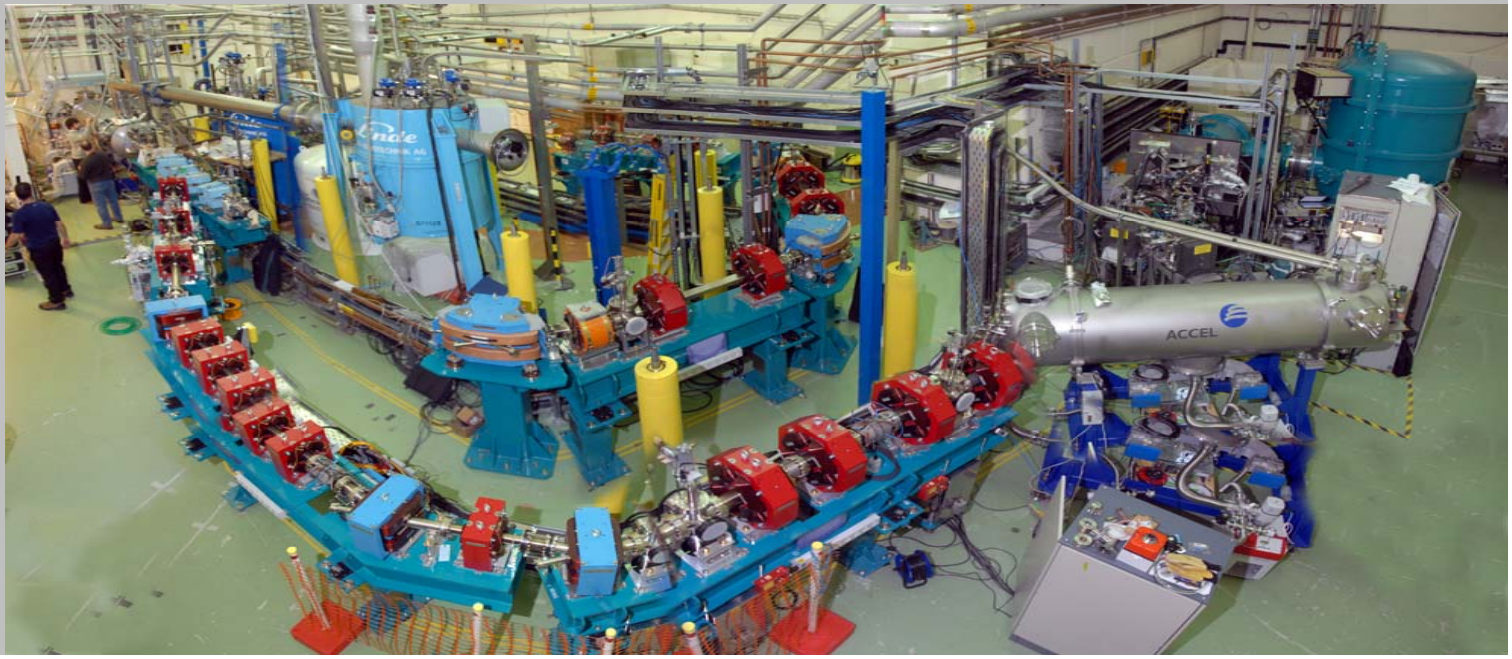
- All modules are under vacuum
- Two modules share some components with the gun diagnostic line



ERLP takes shape



March 2007

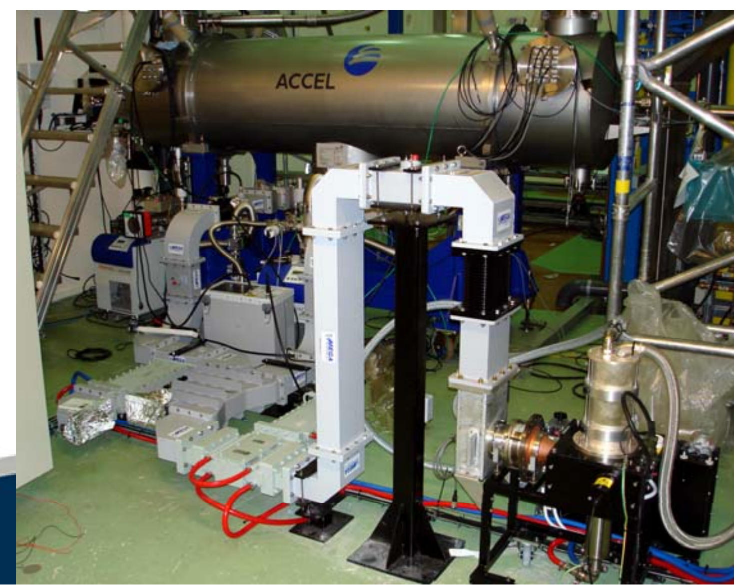


ERLP first e-beam

1:08 am Wednesday 16th August 2006

- First electrons from the photoinjector and further commissioning continuing
- Linac & booster modules cooled down to 2K
- Stable operation of the cryogenics plant at 2K
- High power RF commissioning underway.

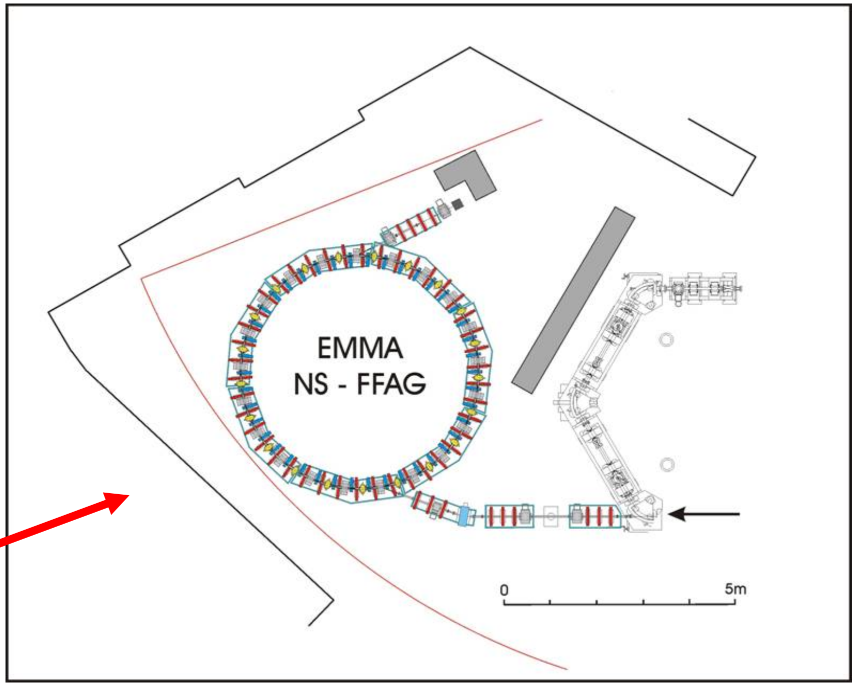
Planning for energy recovery by Christmas

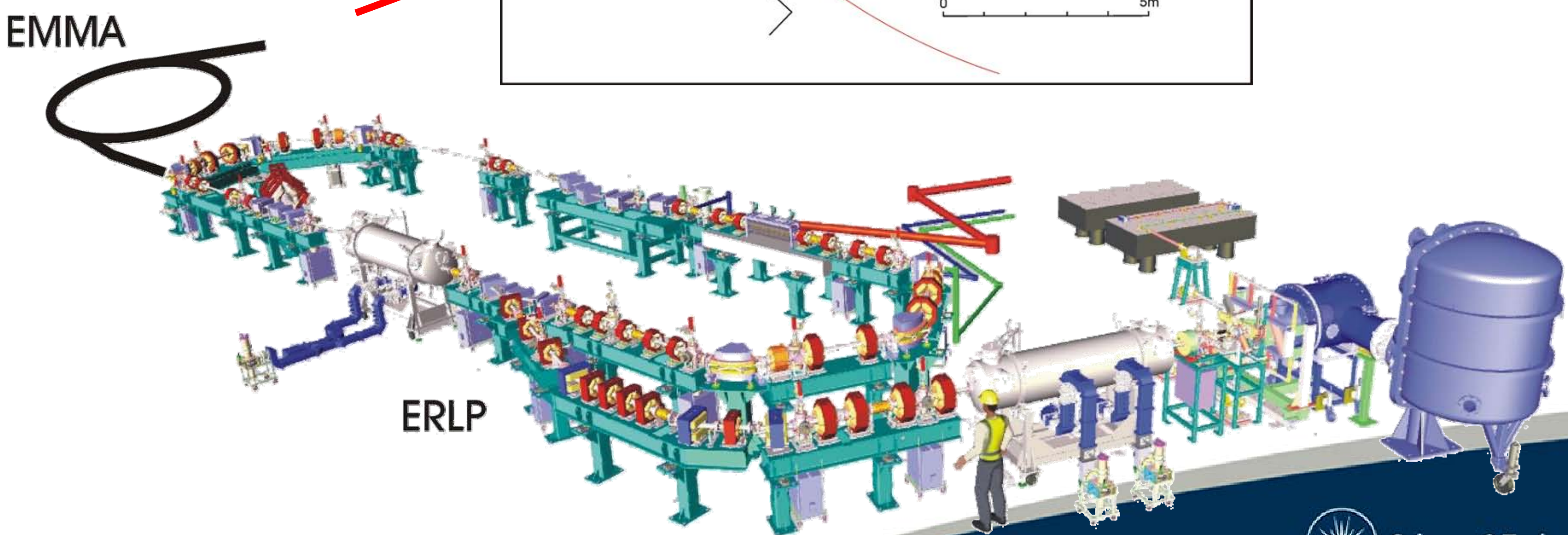


Future Plans

- Confirmation linac gradient July
- Confirmation booster gradient end August
- Gun & diag line studies finished Mid Sept
- Booster repositioned Late Sept
- Beam through booster Oct
- Beam through the linac end Nov
- **Energy recovery demonstrated** Christmas!
- 2008:
- Compton backscatter phase 1
- THz production
- Install wiggler
- Energy recovery from FEL-disrupted beam
- Produce output from the FEL

EMMA – A Non-Scaling FFAG Accelerator





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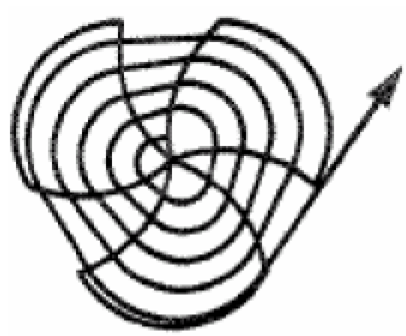
What is an FFAG?

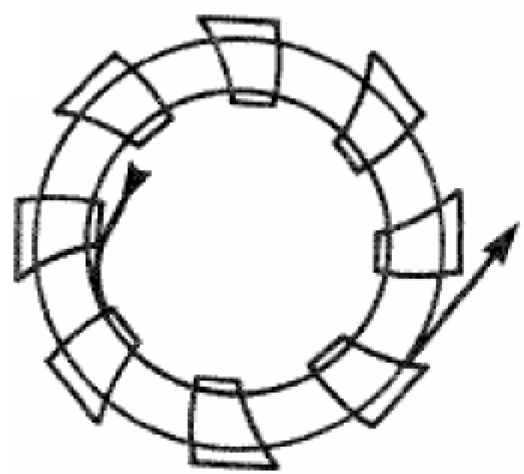
Fixed magnetic field – members of the cyclotron family

Magnetic field variation B(θ)	Fixed RF frequency (CW operation)	Frequency modulated (pulsed beam)
Uniform	Classical	Synchro-
Alternating	Sector-focused	FFAG

FFC + SC



SFC

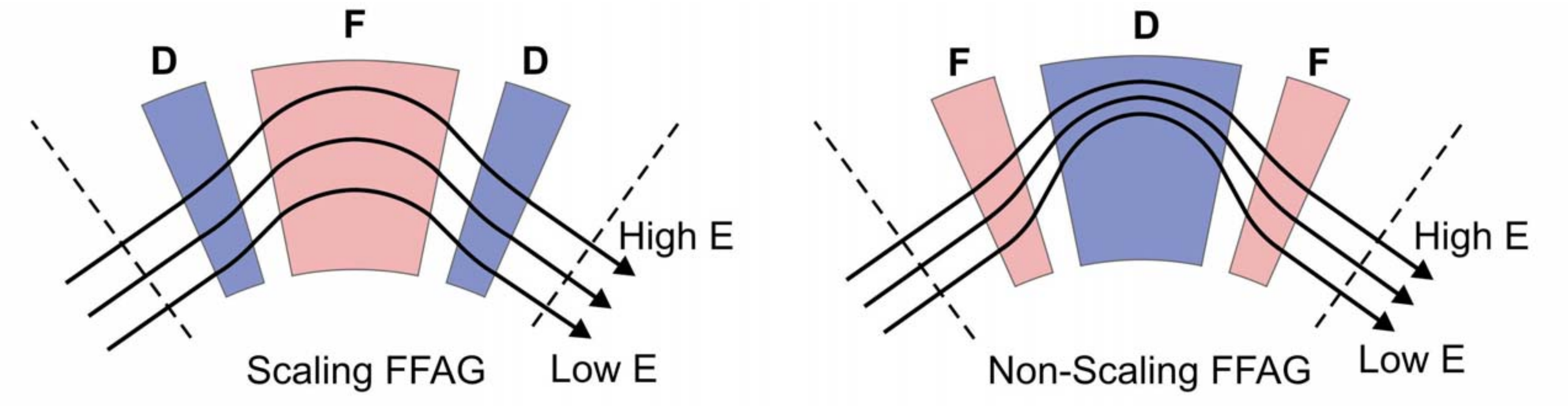


FFAG

EMMA

What is a non-scaling FFAG?

- Scaling FFAGs have radius proportional to energy (a ‘modulated cyclotron’
- Non-scaling don’t have proportional radius – smaller magnet apertures.
  - As the energy goes up, you cross lots of resonances but only in 10-30 turns (depending on the RF voltage); not really sure what is going to happen
  - No-one has built one, so we are going to!



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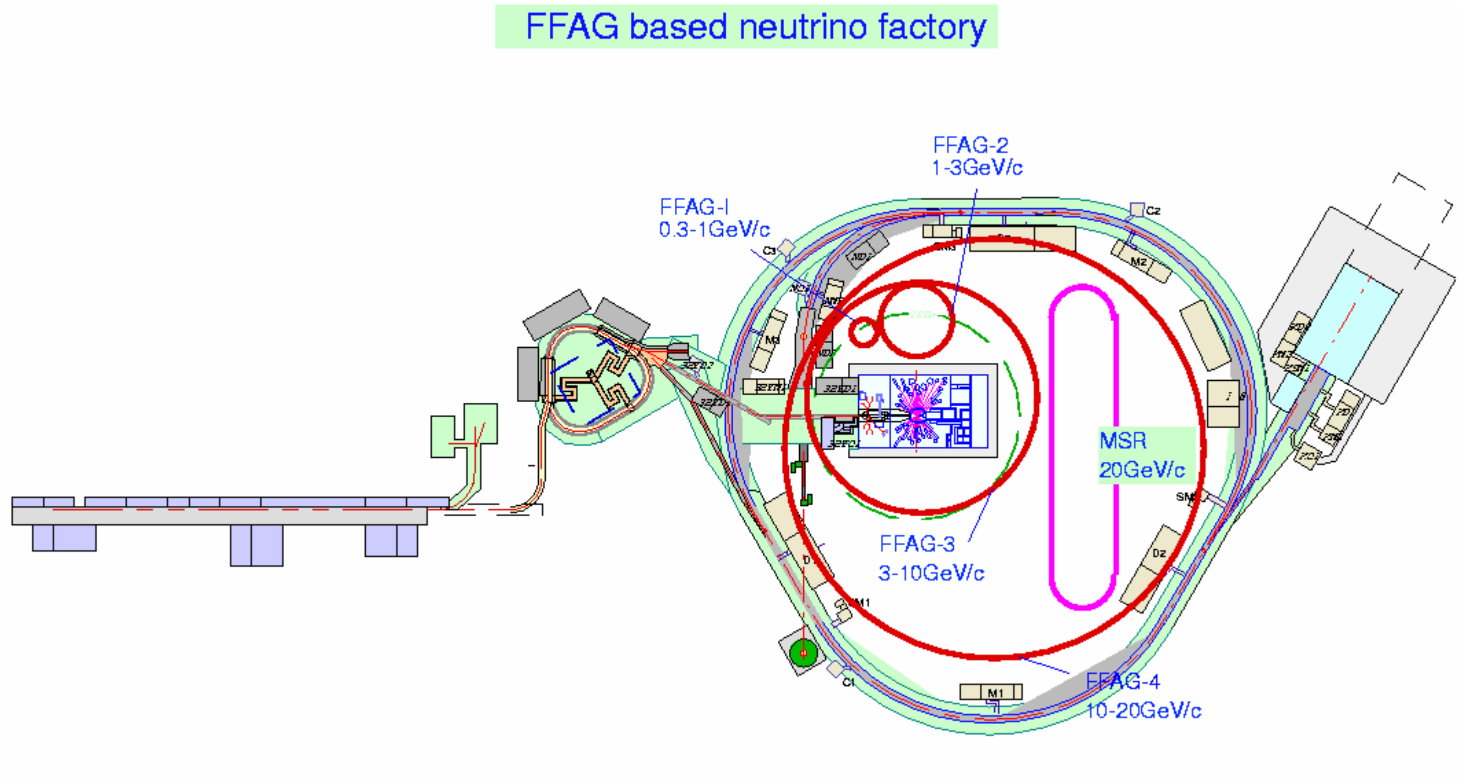
Why a non-scaling FFAG?

- Two motivations:
  - Cheap, fast acceleration of muons – EMMA a model of this
  - Cheap proton acceleration for radiotherapy – PAMELA proposal



EMMA Cell Layout

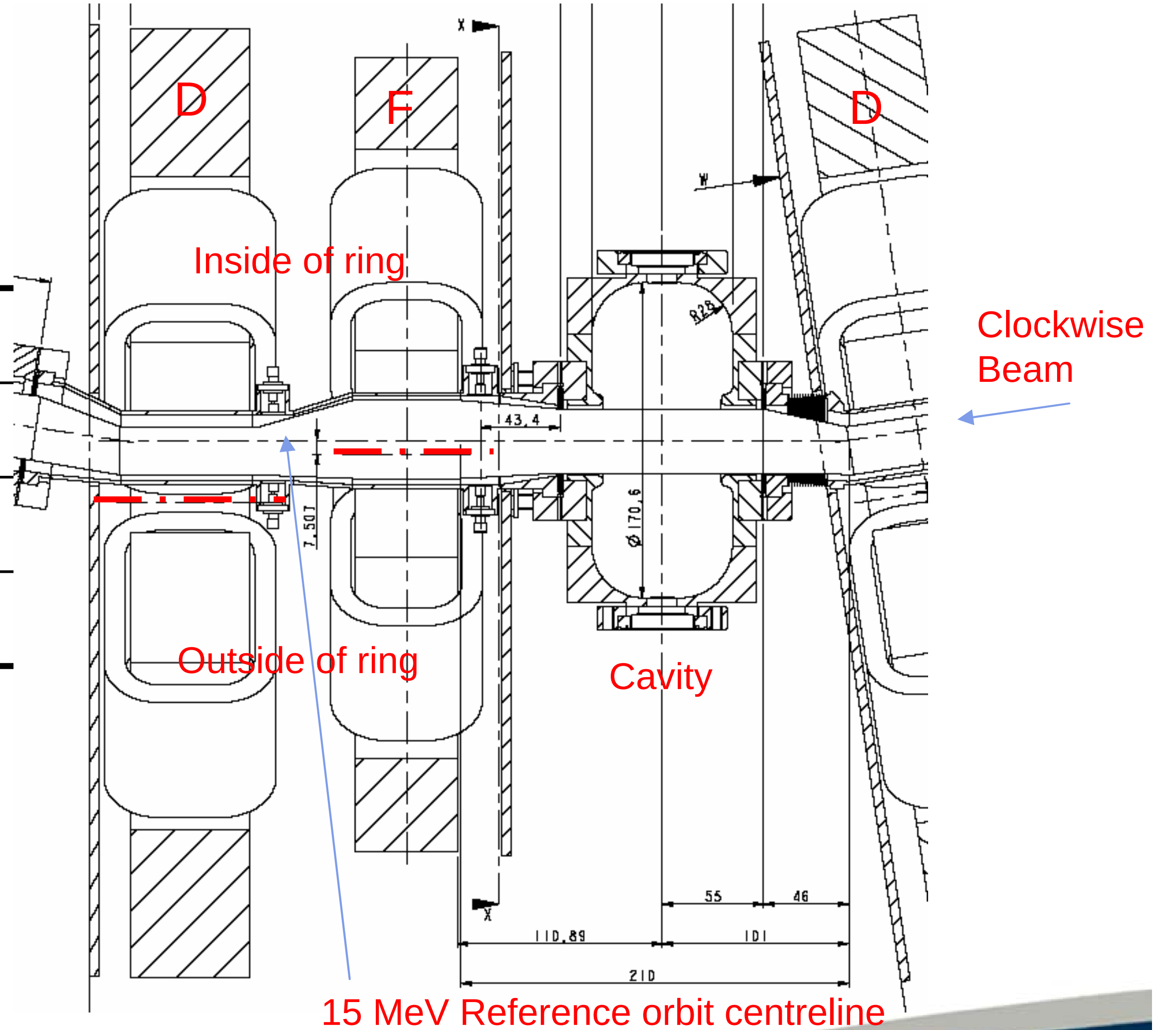
Geometry consisting of 42 identical(ish) straight line segments of length 394.481 mm

Long drift	210.000 mm
F Quad	58.782 mm
Short drift	50.000 mm
D Quad	75.699 mm

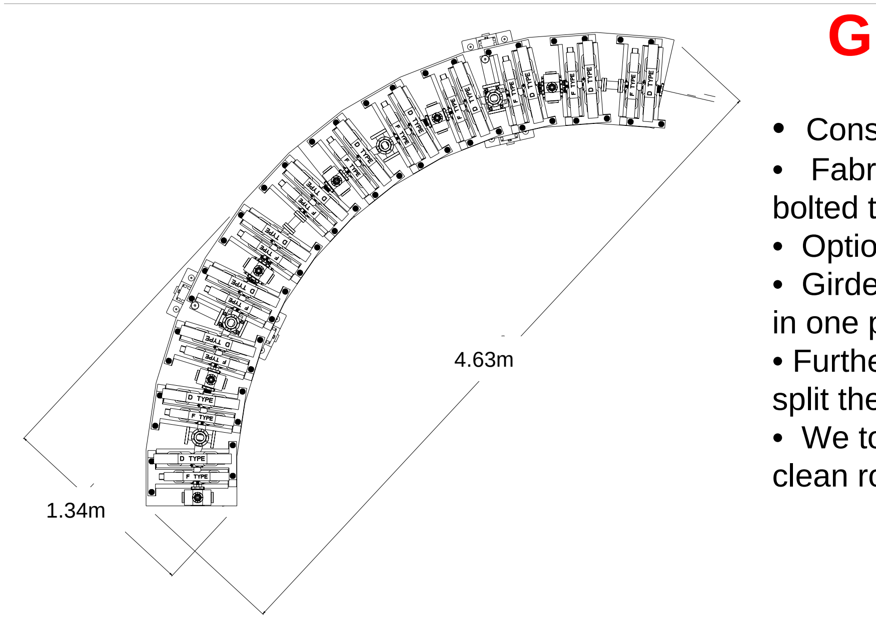
Circumference = **16.568m**

Magnet Reference Offsets
D = 34.048 mm
F = 7.514 mm

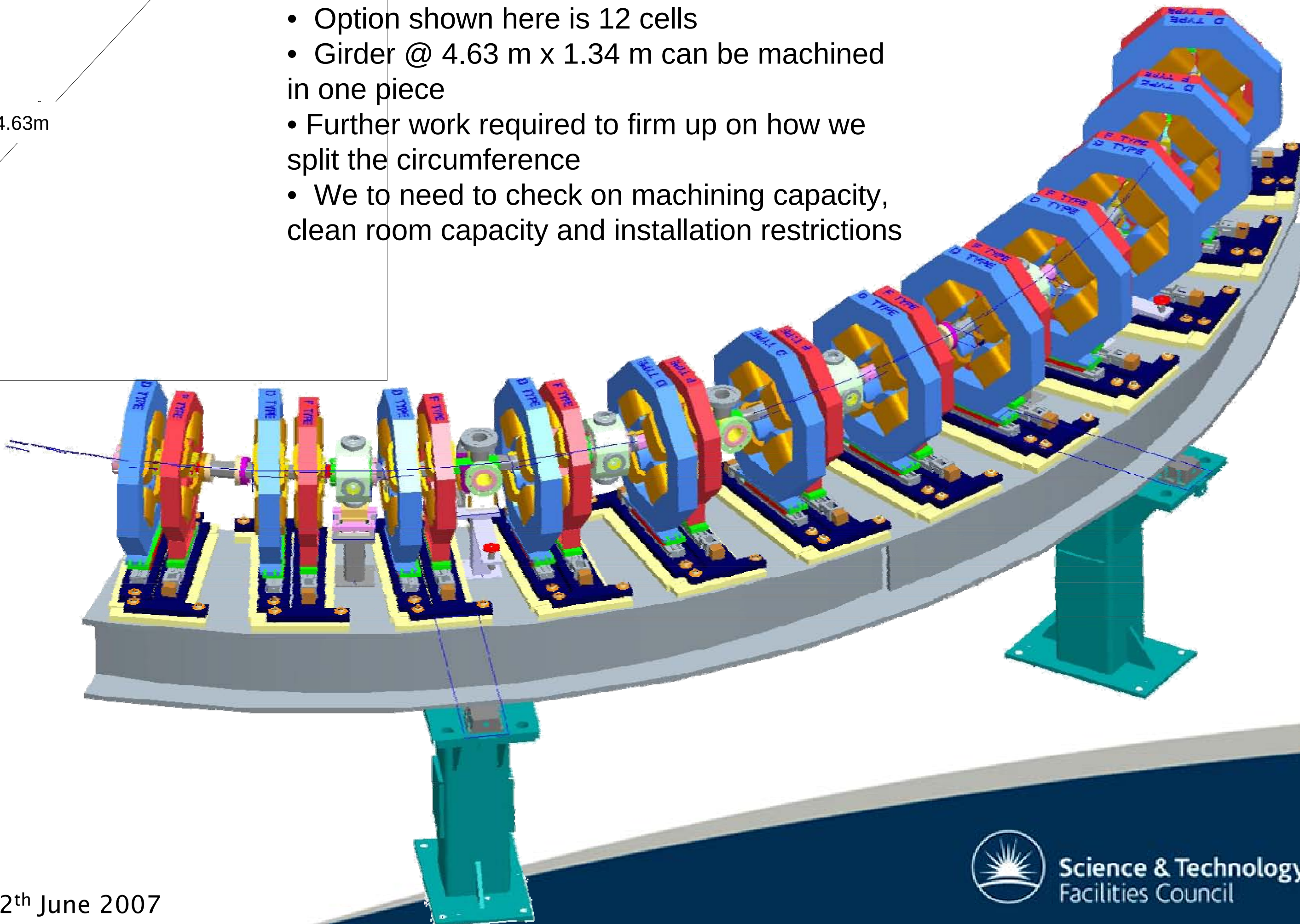
Magnet Yoke Lengths
D = 65 mm
F = 55 mm



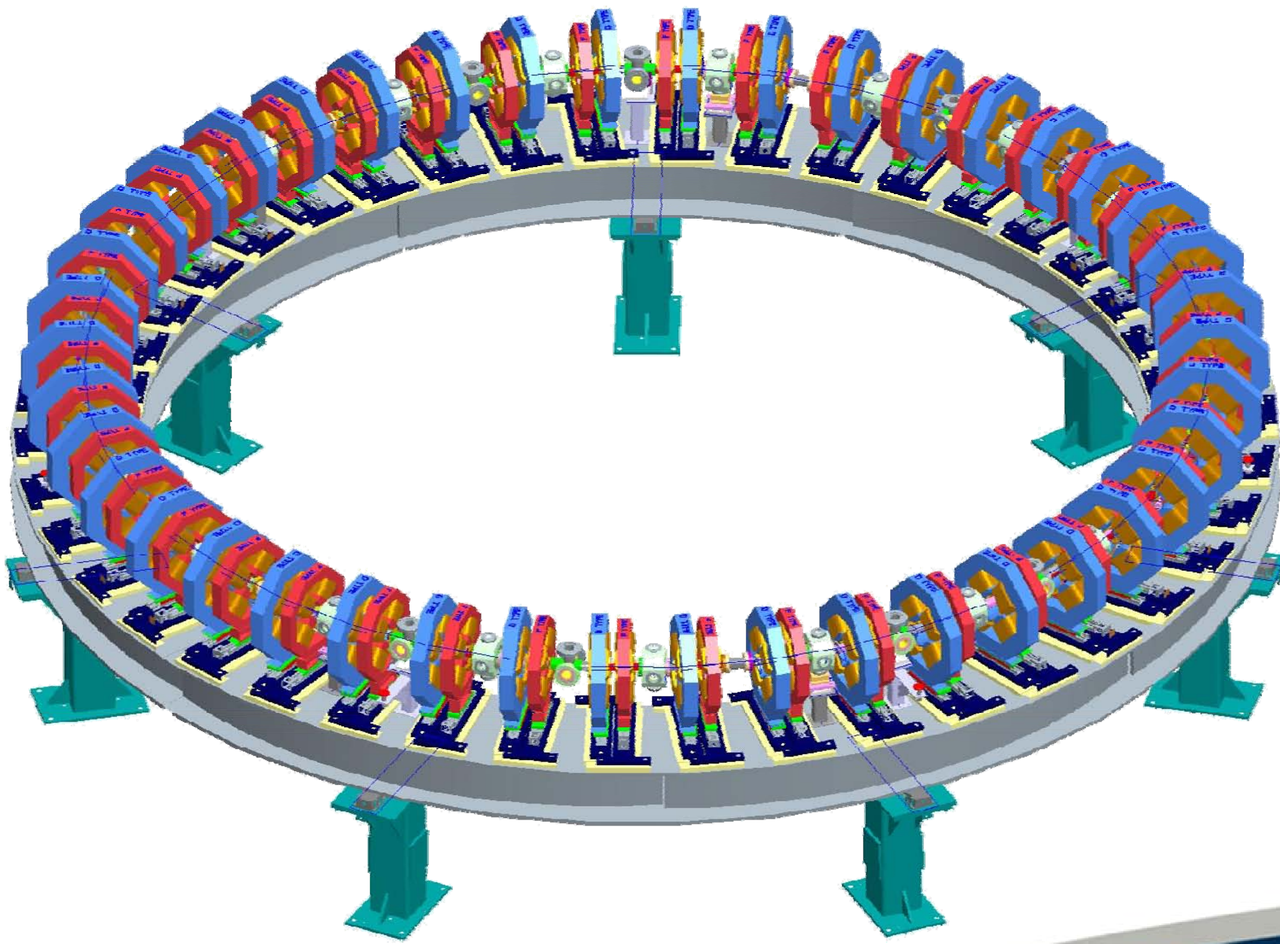
Girder Assembly



- Considering 1 girder support approach
- Fabricated from 3 or 4 pieces, machined an bolted together to make a rigid ring
- Option shown here is 12 cells
- Girder @ 4.63 m x 1.34 m can be machined in one piece
- Further work required to firm up on how we split the circumference
- We to need to check on machining capacity, clean room capacity and installation restrictions

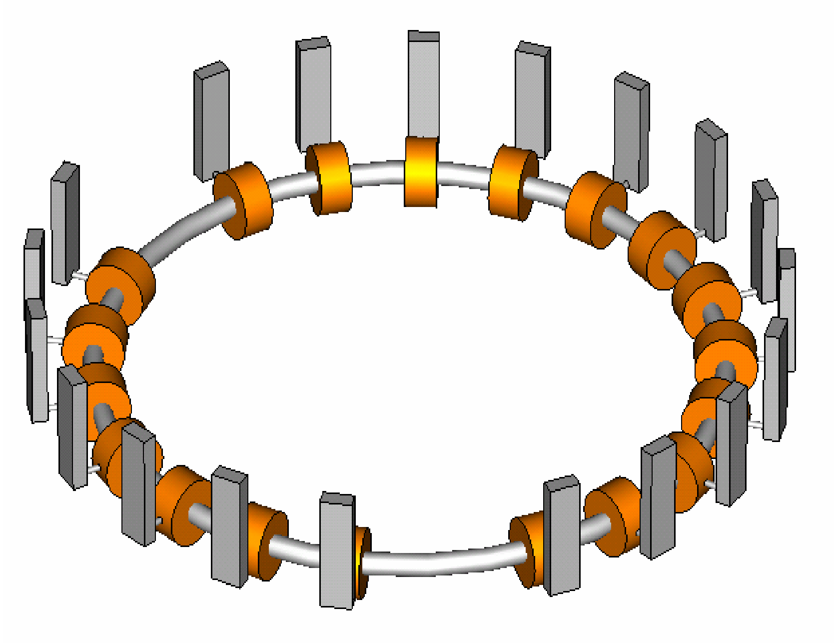


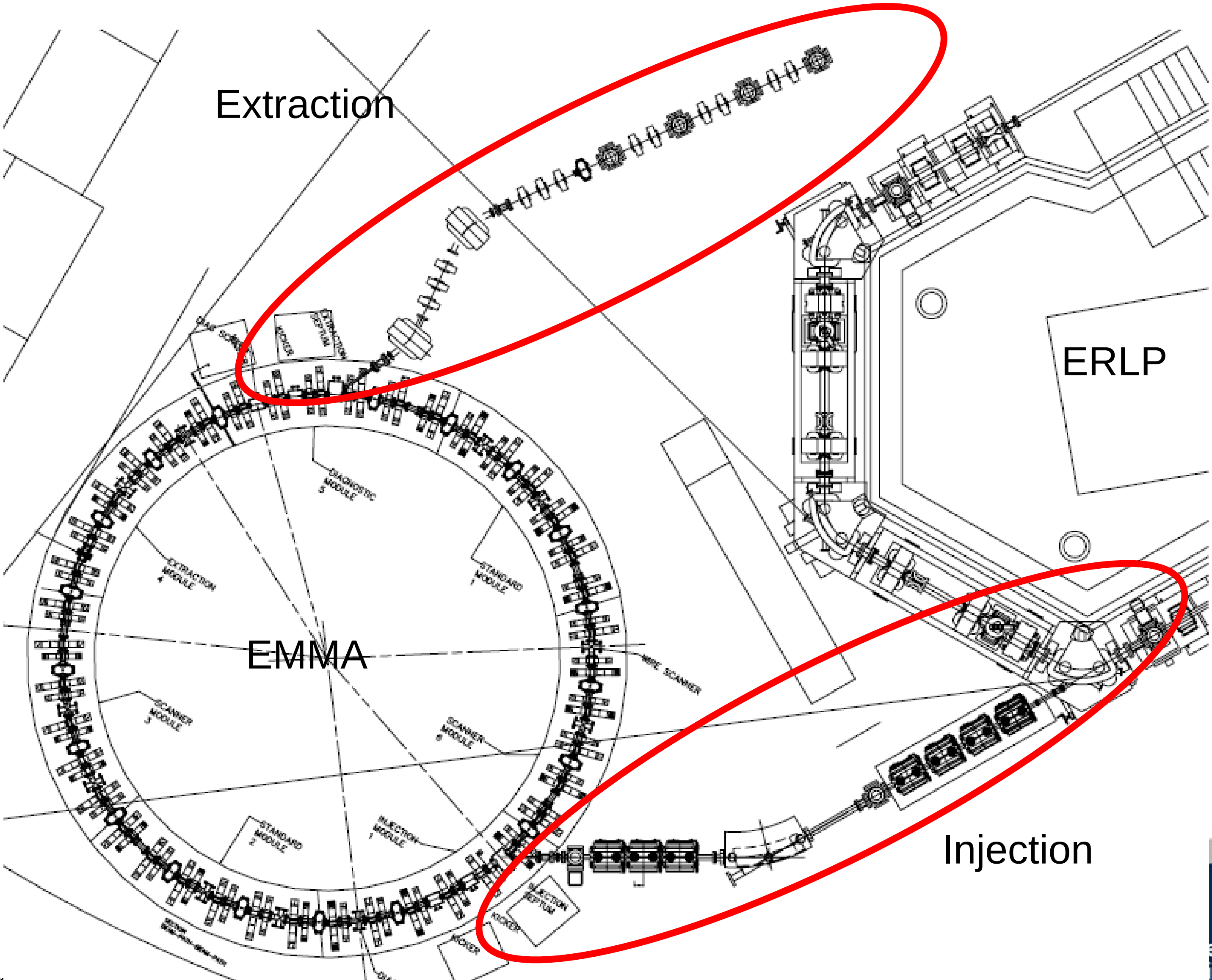
EMMA Ring



EMMA – RF Provision

Machine Parameters	Value
Frequency (GHz)	1.3
Number of Straights	21
Number of Cavities	19
Total Acc per turn	2.3 MV
Upgrade Acc per turn	3.4 MV
Beam Aperture	40mm
RF Bunch Length	1.6 ms
RF Repetition rate	10 Hz
Phase Control	0.02°
Amplitude Control	$2x10^{-4}$




Extraction
ERLP
EMMA
Injection