ERLP Status January 2007

Lee Jones
ASTeC

ERLP Progress Update: Content

- Introduction
- Construction status
- Injector commissioning
- Accelerating modules & Cryogenics
- Beam transport system
- Ongoing work
- Future plans
- X-Ray production & EO diagnostics on the ERLP
- The EMMA NS-FFAG project

ERL Prototype: Technical Priorities

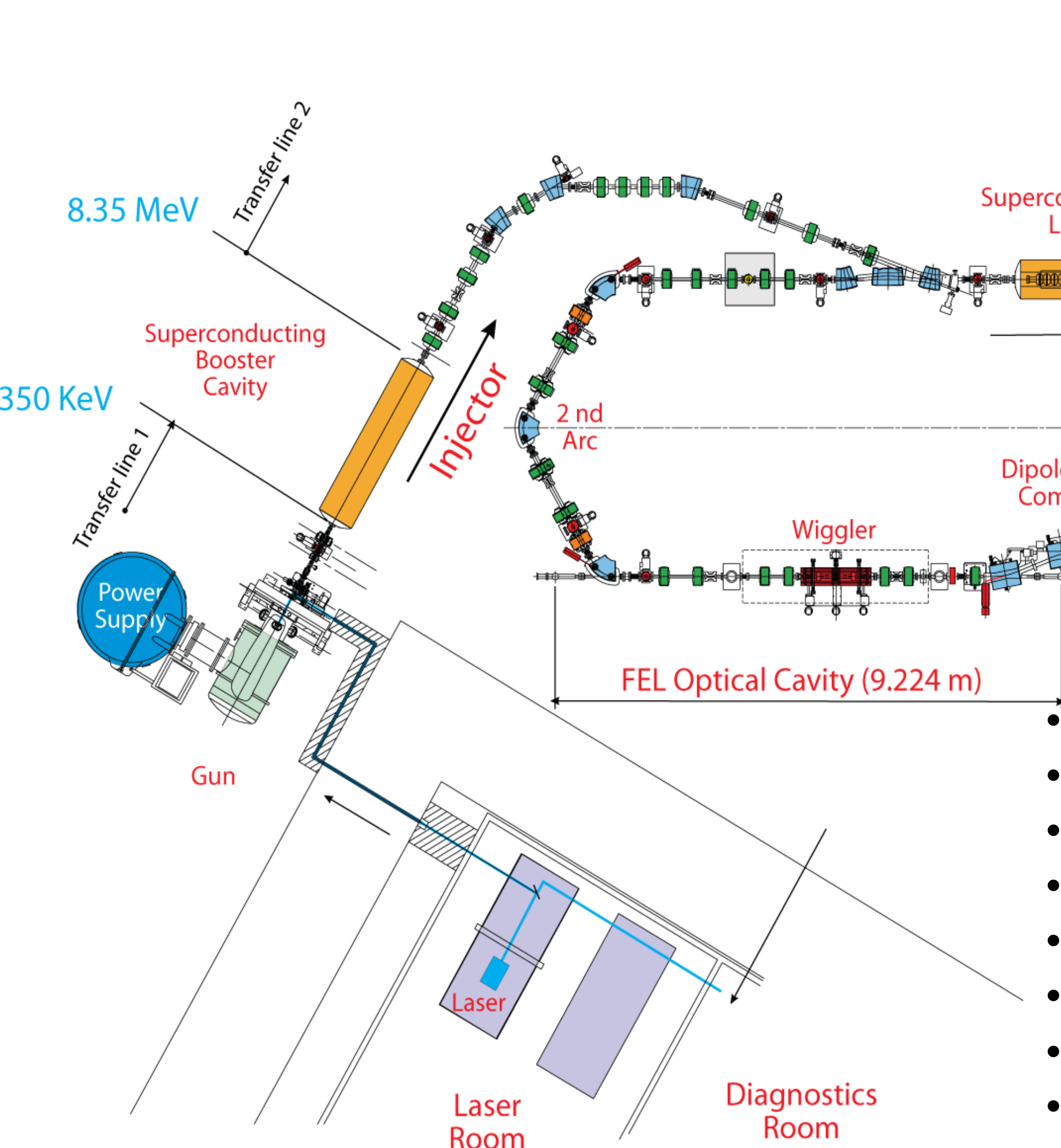
Primary Goals:

1. Foremost: ***Demonstrate energy recovery***
2. Produce and maintain bright electron bunches from a photoinjector
3. Operate a superconducting LINAC
4. Produce short electron bunches from a compressor

Further Development Goals:

1. Demonstrate energy recovery during FEL operation (with an insertion device that significantly disrupts the electron beam)
2. Develop a FEL activity that is suitable for the synchronisation challenges and needs expected of 4GLS
3. Produce simultaneous photon pulses from a laser and an ERLP photon source which are synchronised at or below the 1 ps level

ERL Prototype: Accelerator Layout



• Nominal gun energy	350 keV
• 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
• Maximum average current	13 µA

Construction Status

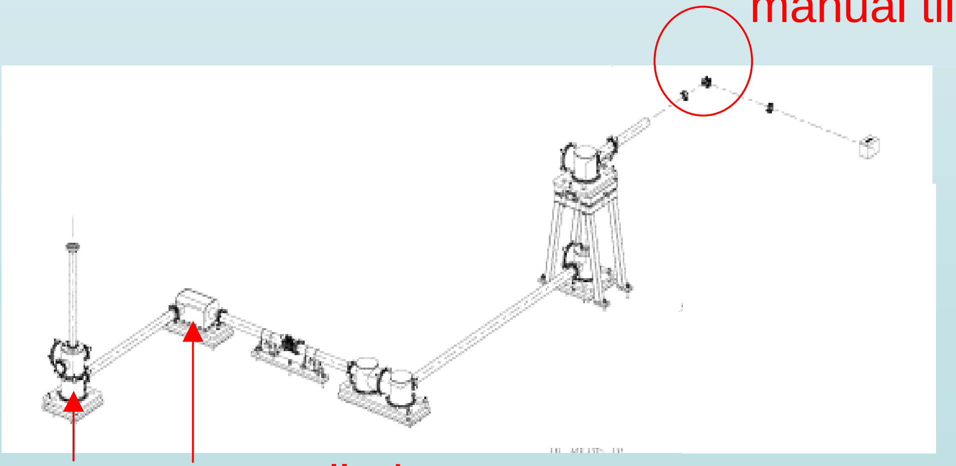
- Photoinjector laser system delivering beam to cathode since April 2006
- Gun installed with a dedicated gun diagnostic beamline
- Both superconducting modules delivered from Accel
- Cryosystem installed by Linde and DeMaco, and used to cool accelerating modules down to 2 K
- All but two of the beam transport modules are present in the Tower, awaiting installation

Laser: Summary

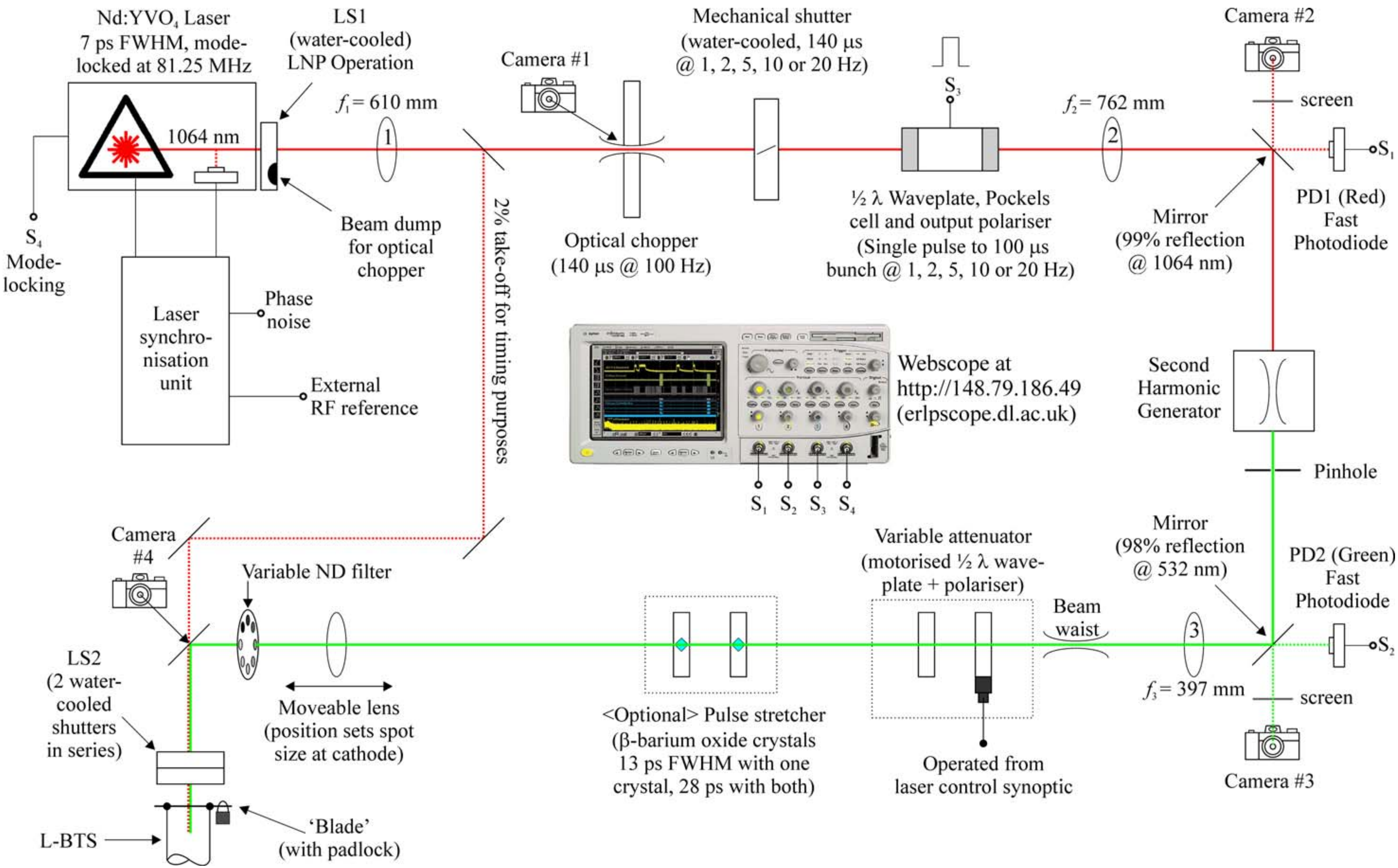
- $Nd:YVO_4$ - Wavelength: 1064 nm, doubled to 532 nm
- Pulse energy: 20 nJ on target (required)
- Pulse duration: 7, 13, 28 ps FWHM
- Pulse repetition rate: 81.25 MHz
- Macropulse duration: 20 ms (100 µs @ 20 Hz)
- Duty cycle: 0.2%
- Timing jitter: < 400 fs
- Spatial profile: Circular top-hat on photocathode

✓ Laser system commissioned at Rutherford Lab in 2005

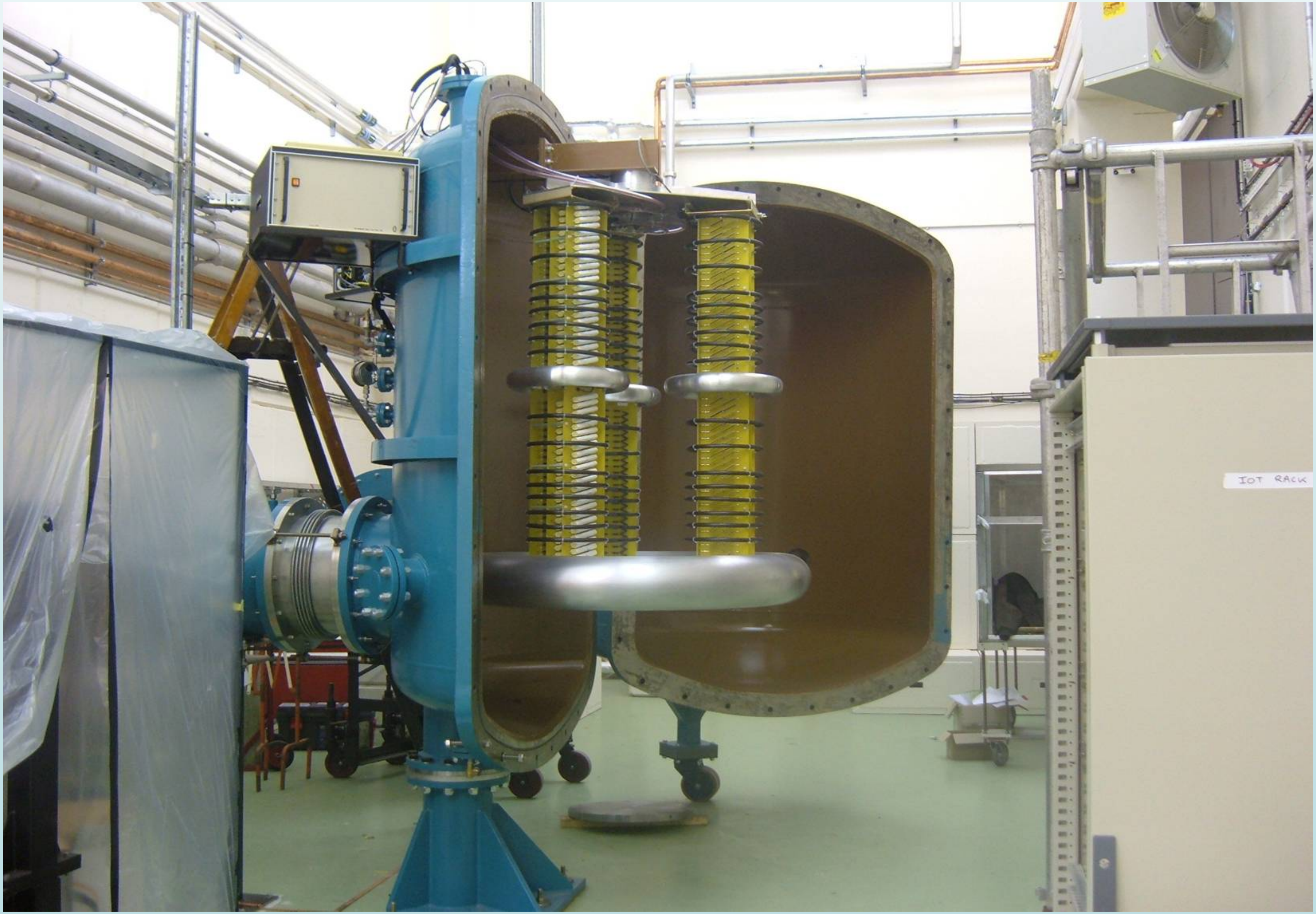
✓ Laser & transport commissioned at Daresbury Lab in April 2006



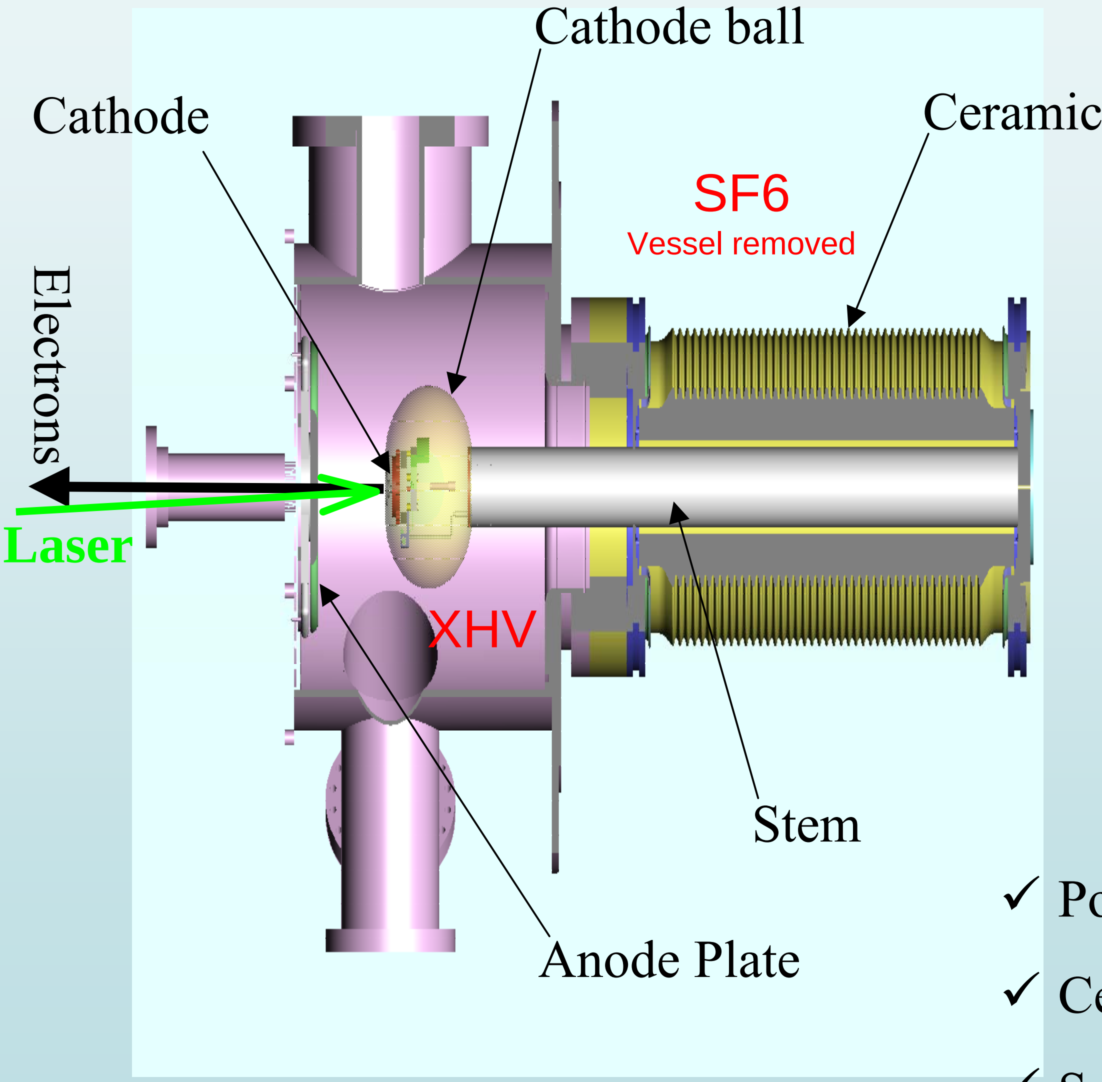
Laser: Overview



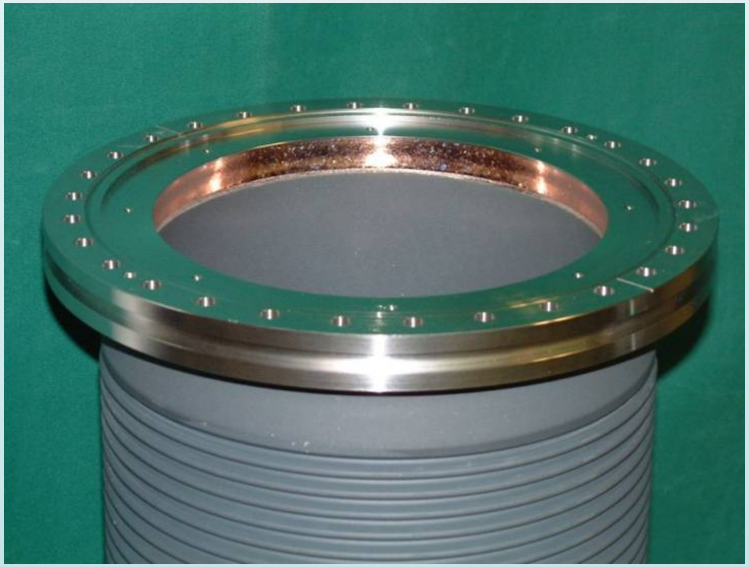
Gun Power Supply



Gun Assembly

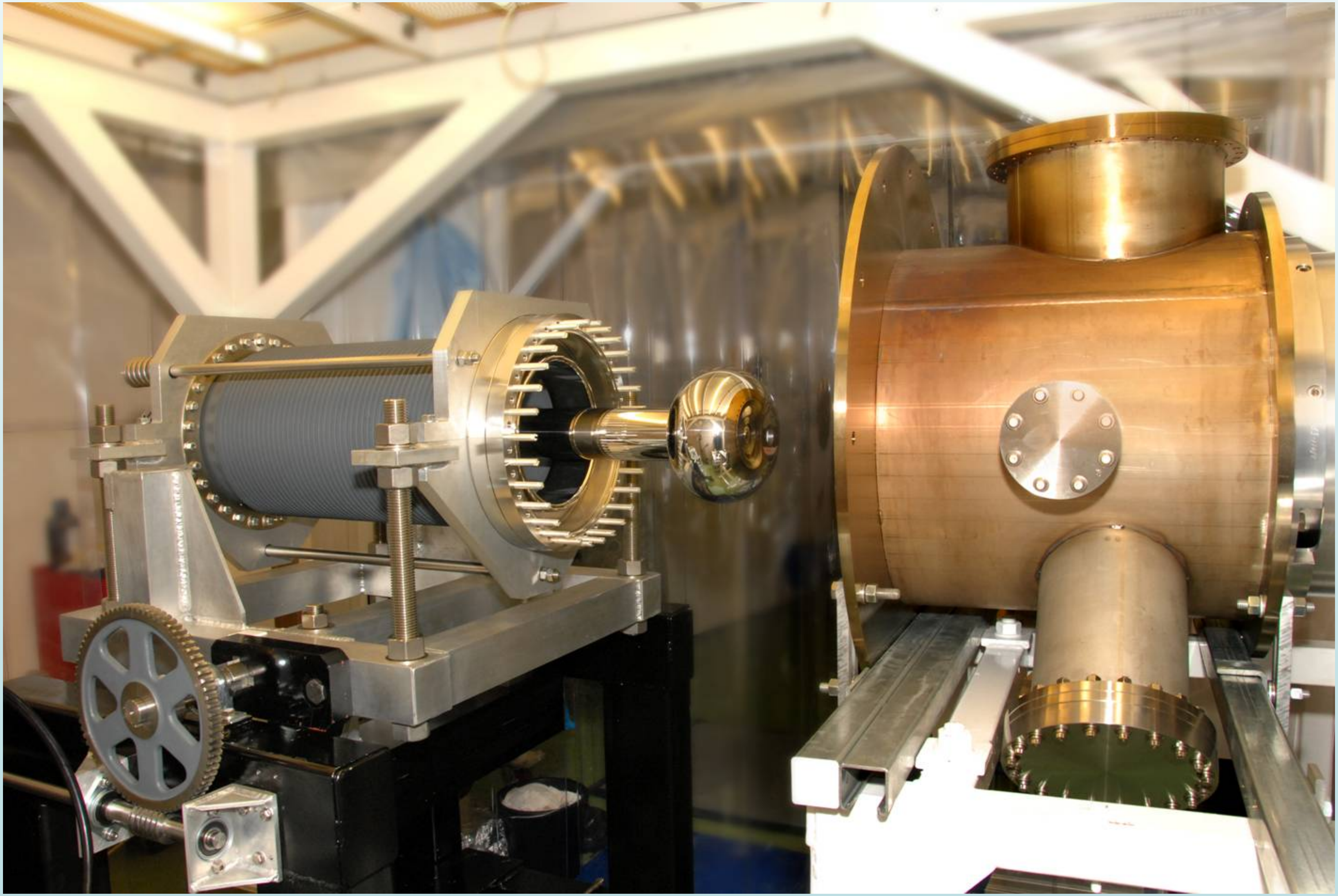


- JLab design GaAs cathode
- 500 kV DC supply
- Target transverse emittance: ~3 mm mrad



- ✓ Power supply commissioned 2005
- ✓ Ceramic delivery March 2006
- ✓ Spare ceramic delivered Nov 2006

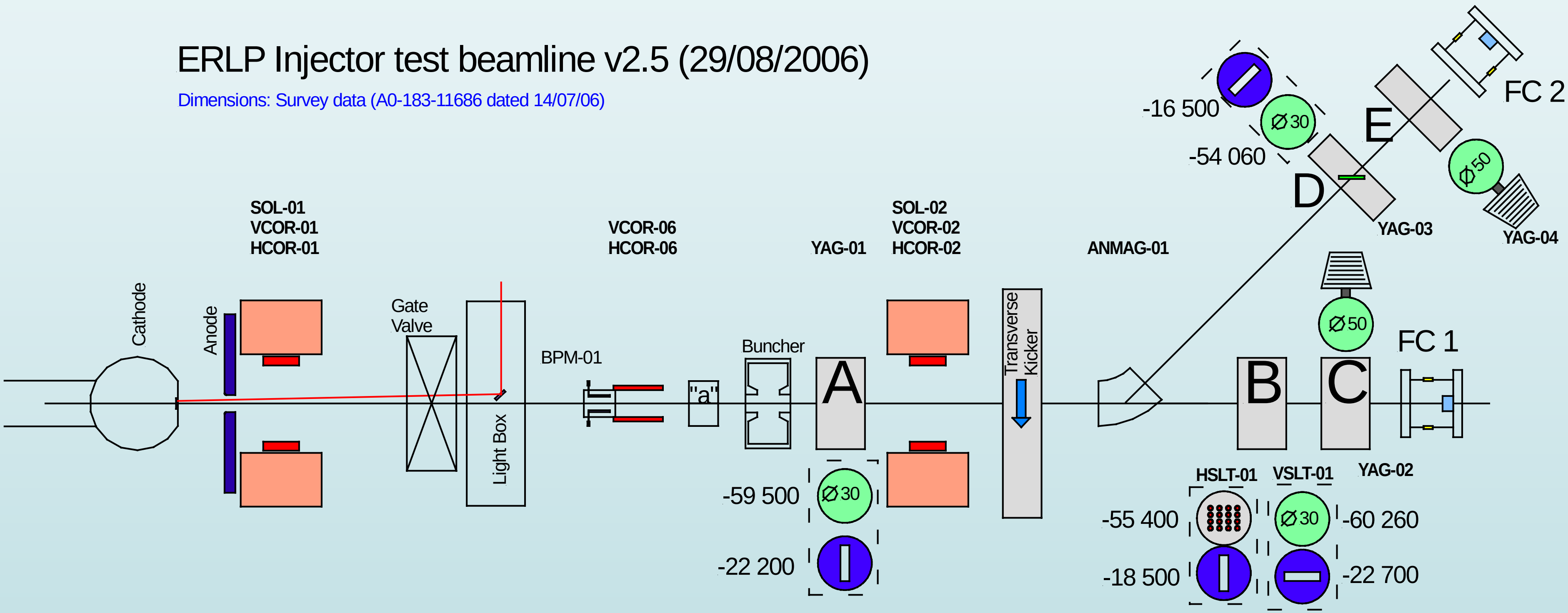
The Insulating Ceramic & Cathode Ball



Injector Diagnostic Line

ERLP Injector test beamline v2.5 (29/08/2006)

Dimensions: Survey data (A0-183-11686 dated 14/07/06)

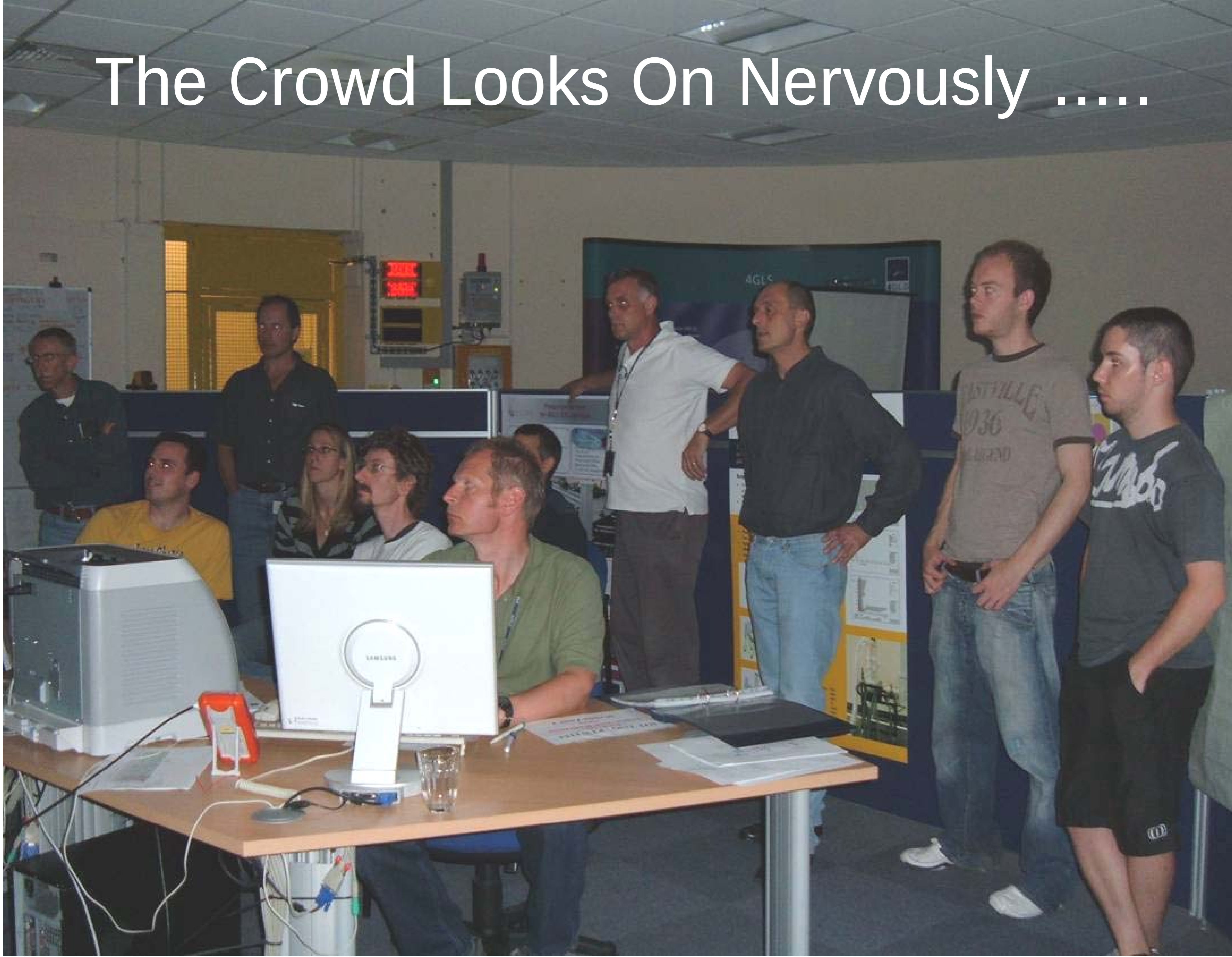


Sections schematics when looking downstream (i.e. from the gun)

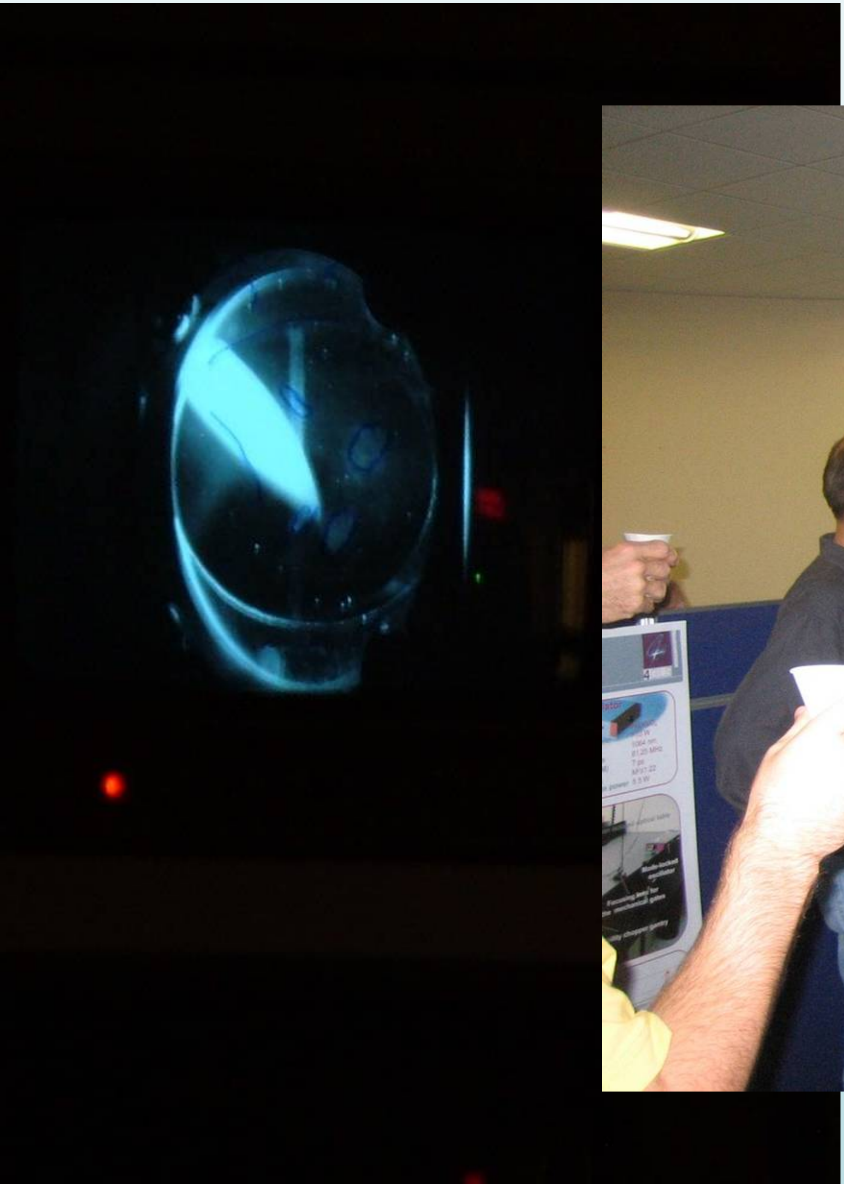
Gun Commissioning Status

- Electron gun operated July and August 2006
- First beam from the gun recorded at 01:08 on Wednesday 16th August with the gun operating at 250 kV
- Operating at 350 kV soon afterwards. Encouraging results obtained
- Following a cathode re-caesiation at the end of August, the Gun was unable to support high voltage during HV conditioning
- Gun was re-baked and still exhibited similar HV breakdown
- Gun was stripped-down, inspected & tested, thoroughly cleaned, re-assembled then baked
- Gun was HV conditioned to 450 kV last weekend (Jan. 6th & 7th)

The Crowd Looks On Nervously .....



First Beam !



JLab Contribution

DL played host to four JLab visitors during the commissioning

- Efficient HV conditioning
- Laser/gun alignment
- Diagnostic line ‘magnetic’ properties
- SF_6 fill and pump systems
- Tuning and steering procedures
- Etc..etc…

Thanks to:

Fay Hannon, Carlos Hernandez-Garcia

Kevin Jordan and George Neil

Performance Achieved So Far

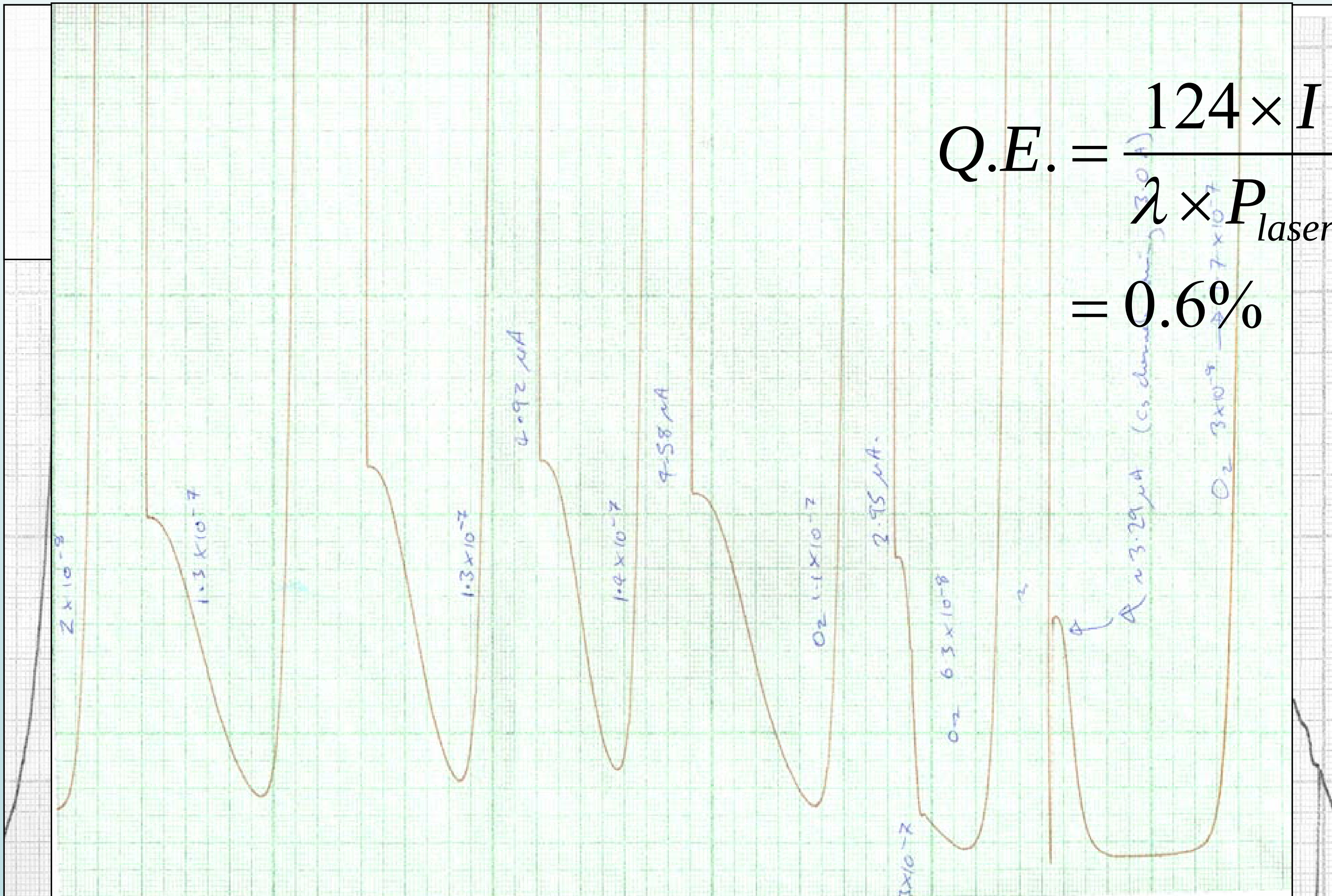
- Beam energy: **350 kV** ✓
- Bunch charge: **5 pC** (ultimate target: 80 pC)
- Quantum efficiency:

  0.4% measured in the gun (ultimate target: 1% to 10%)

  3.5% measured in the offline laboratory chamber

- Bunch train length: **Single 6 ps pulse to 100 μs** ✓
- Train repetition rate: **Up to 20 Hz** ✓

Problems With Caesiation



$$Q.E. = \frac{124 \times I}{\lambda \times P_{laser}}$$

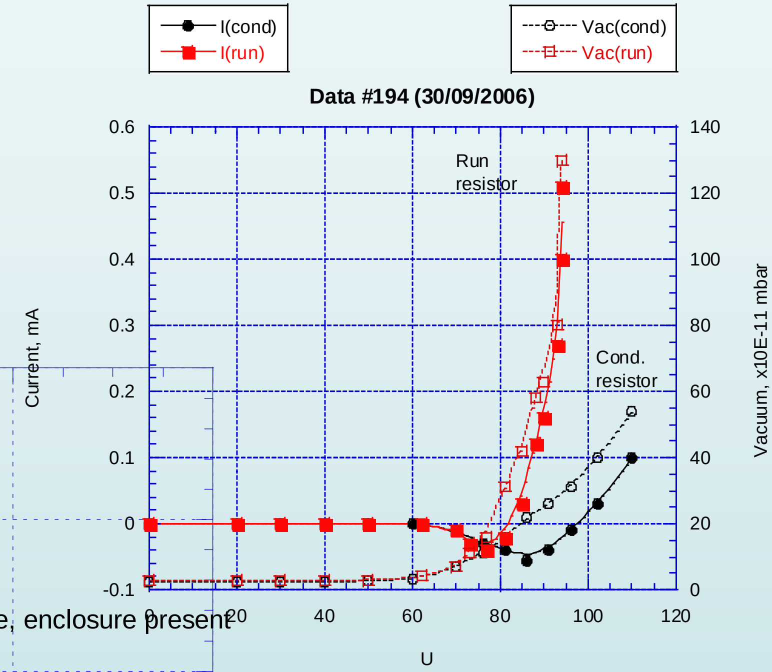
$$= 0.6\%$$

After cathode re-activation on 30/08/06, the gun exhibited huge out-gassing during HV conditioning.

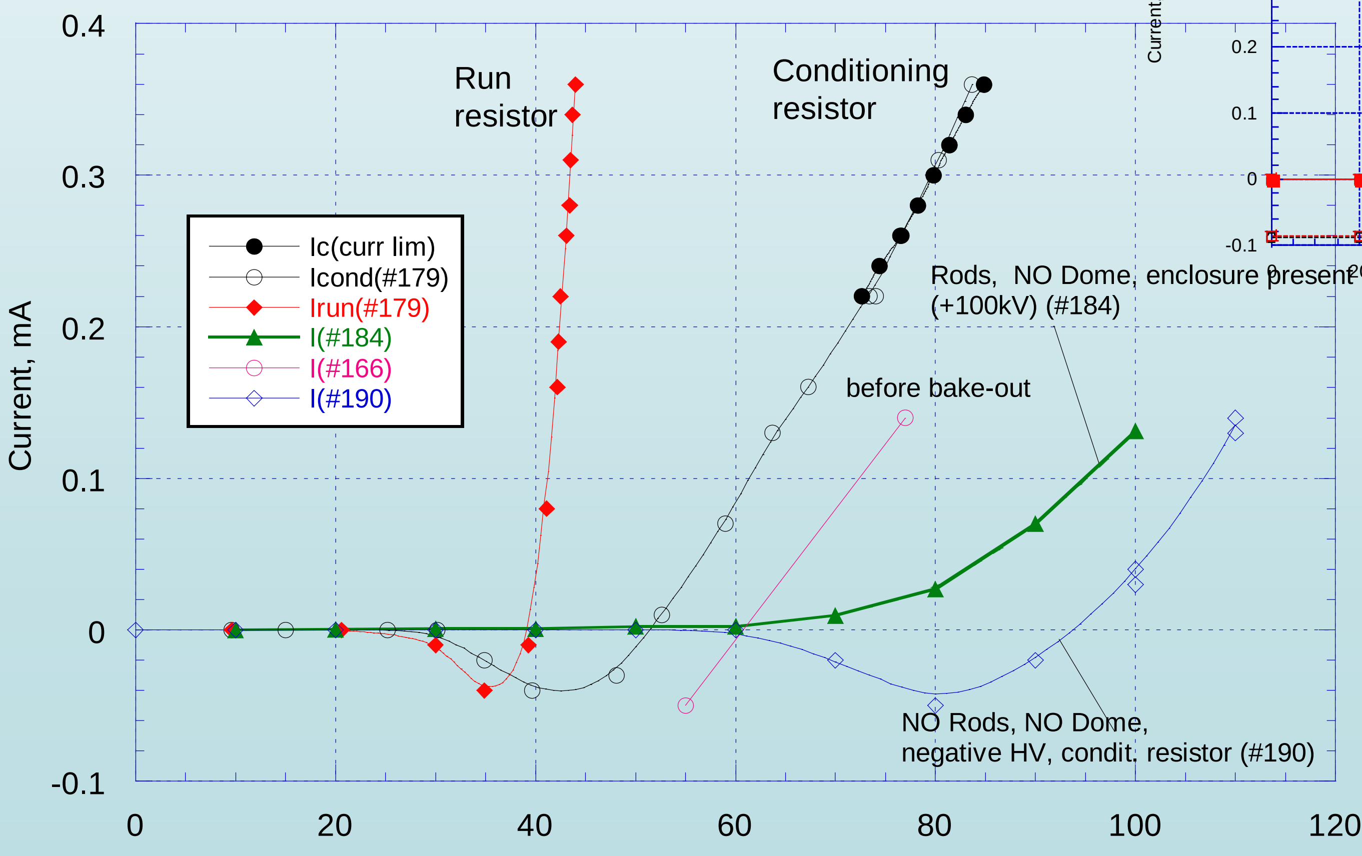
The ensuing vacuum spikes caused frequent HV PSU trips.

On reaching the 320 – 340 kV regime it was clear that the HV PSU current was highly erratic,

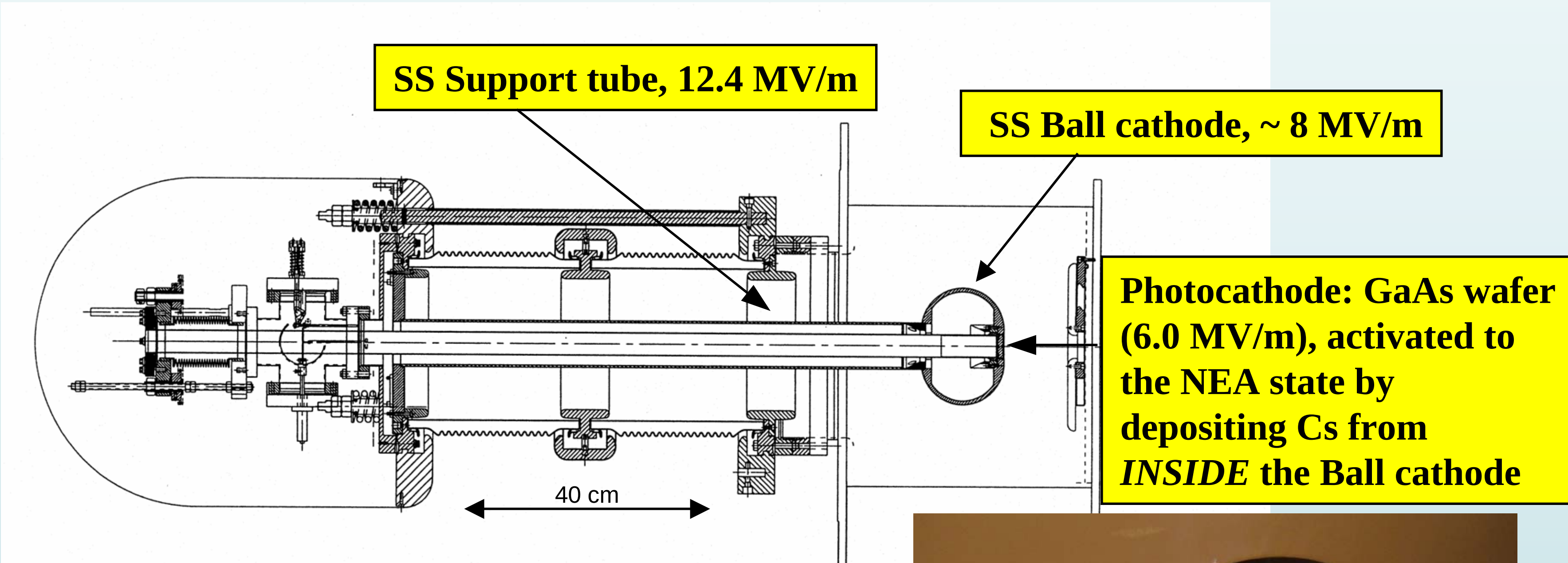
...... and then ……

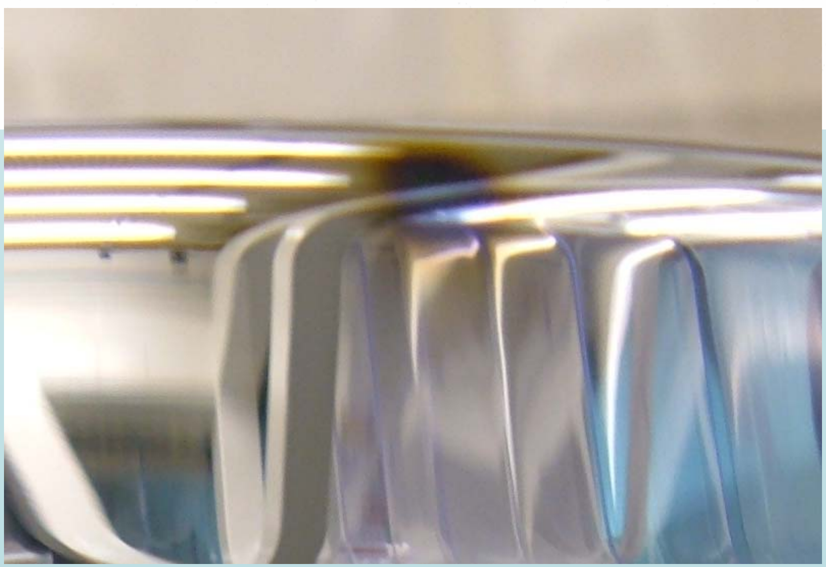


DC Gun HV tests
Data: 20/09/2006 #166,179,184,190

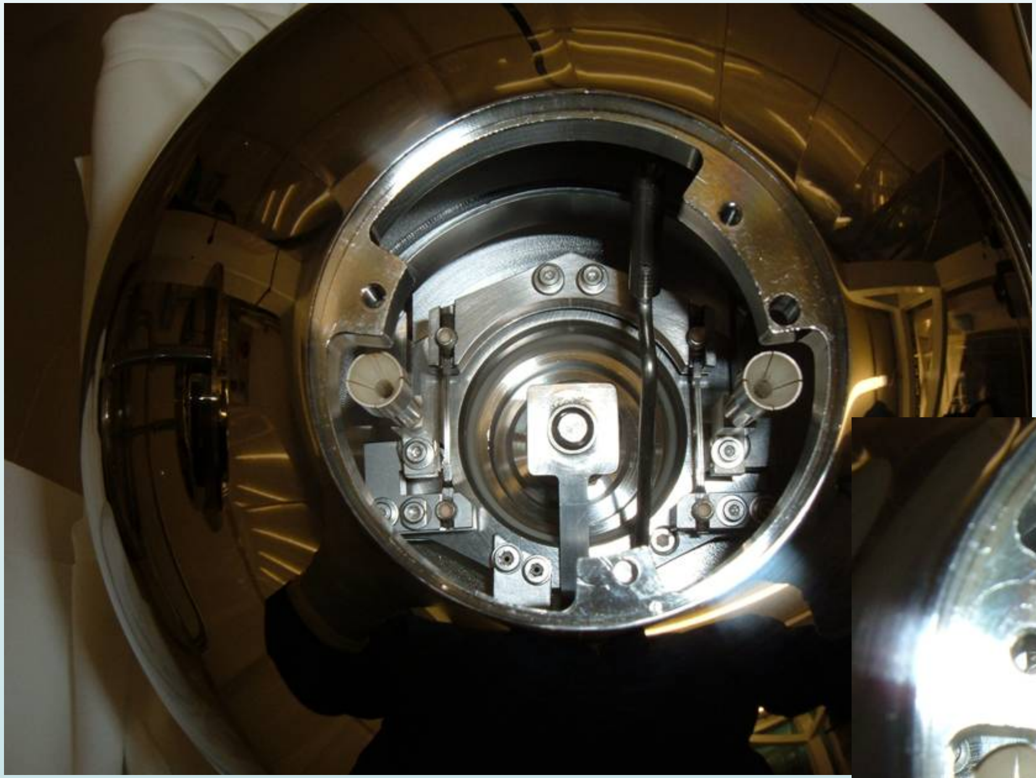


HV Breakdown



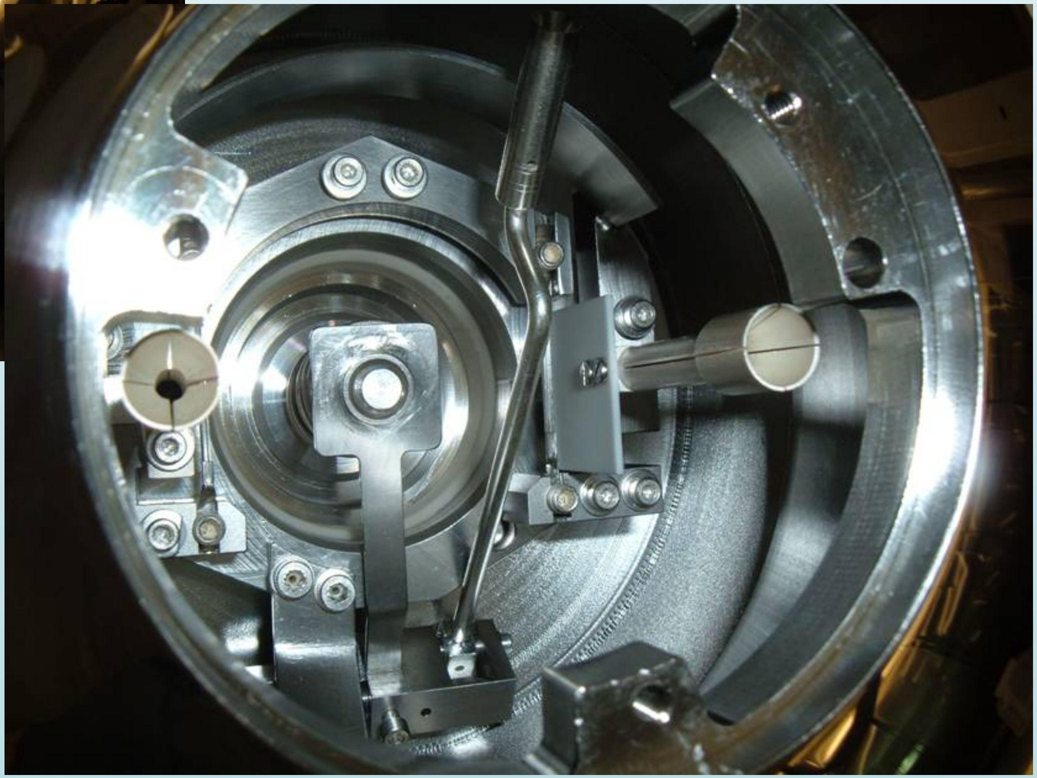


Caesium Channels



Before

After



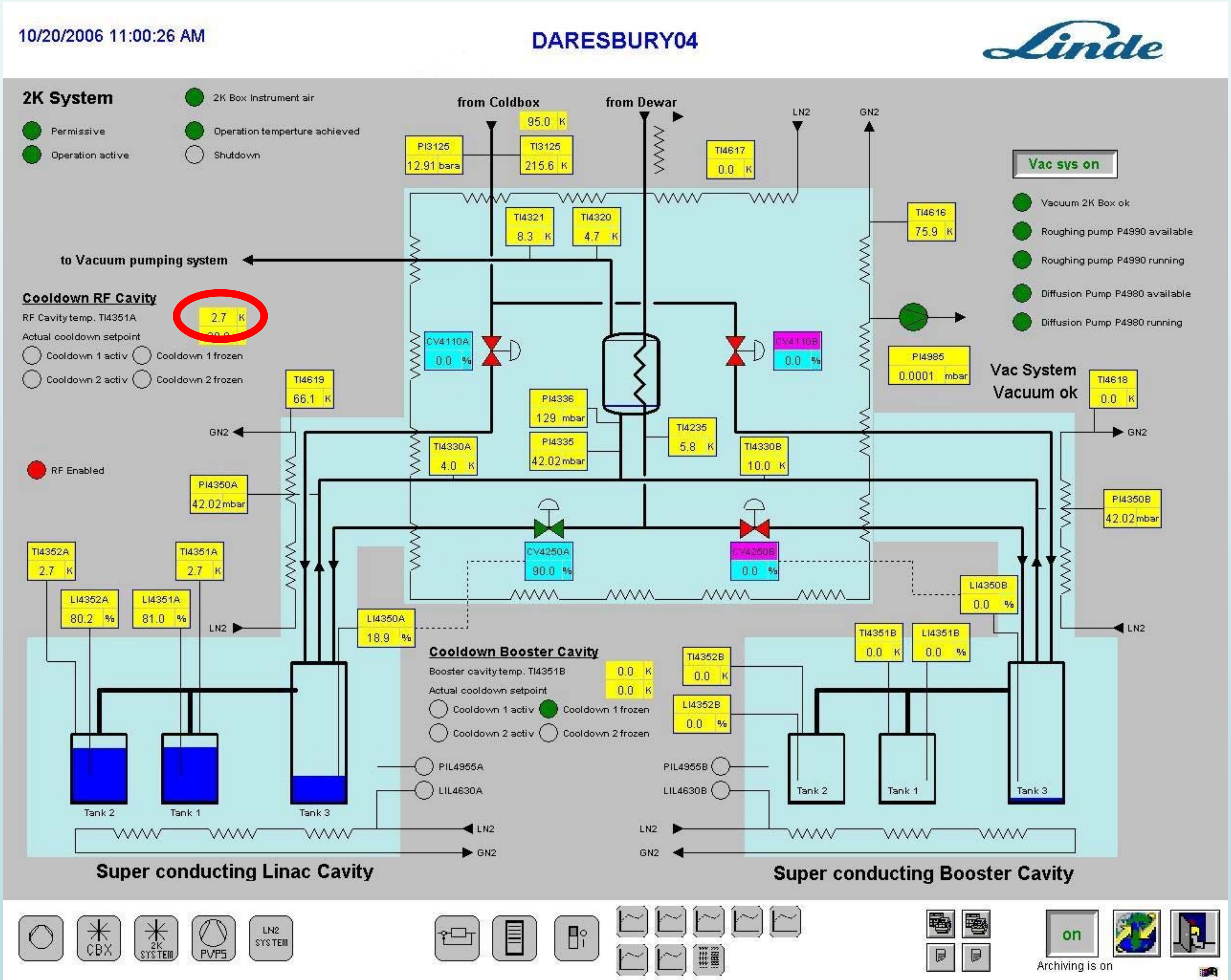
Second Phase Commissioning

- Currently on-schedule to commence the second phase of injector commissioning in January (from this coming weekend)
- Expected 2 weeks of HV conditioning, though 485 kV was reached in a weekend
- Optimisation of laser system in parallel to HV conditioning
- Injector to be operated from mid-January, possibly until the end of February
- Minimum goals have been established for this phase of injector commissioning

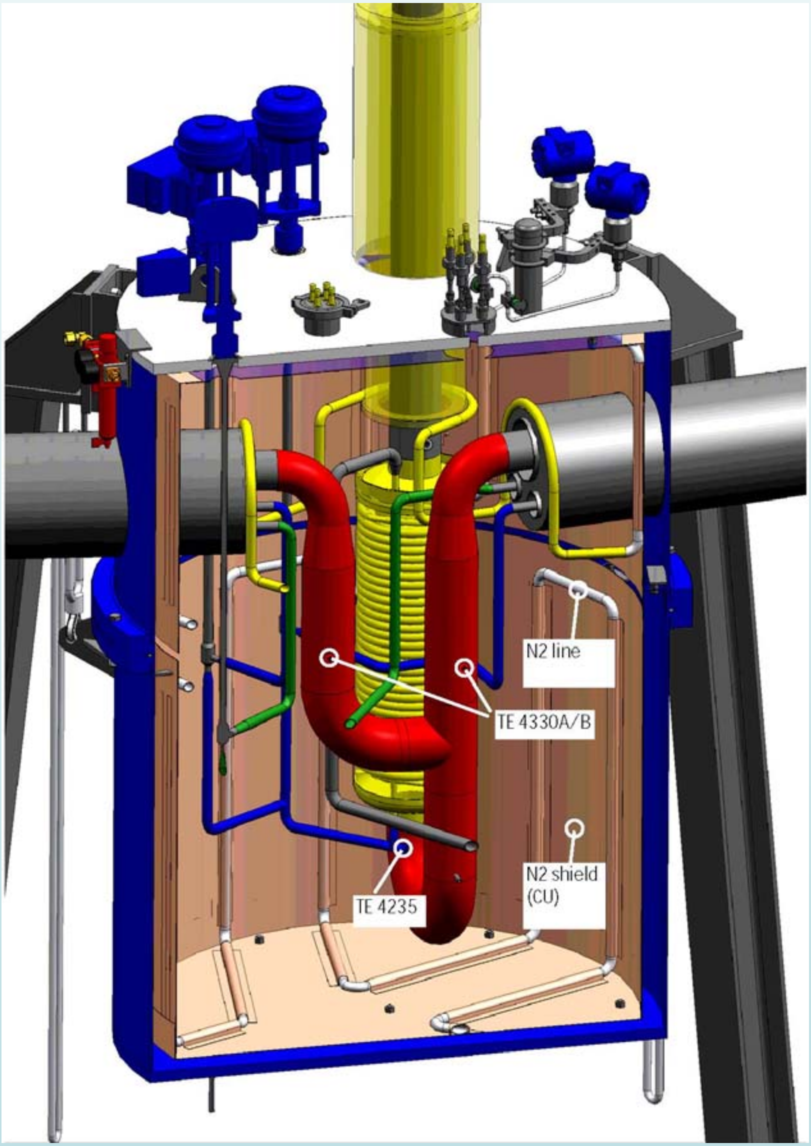
Cryosystem & Accelerating Modules

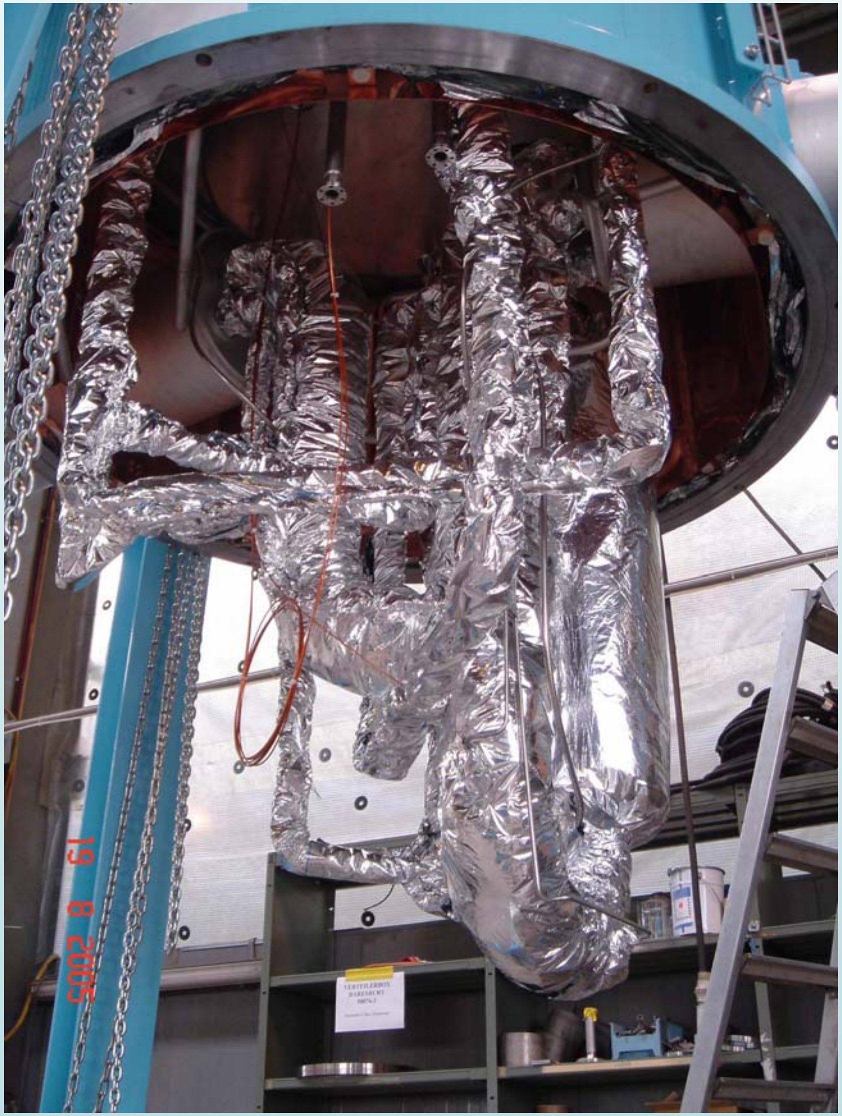
- 4 K commissioning was carried out in May 2006
- ScRF Modules were delivery in April and July
- The modules were cooled *separately* to 2 K, the LINAC in October and the booster in November. In December, both modules were cooled together
- Low-power RF tests have confirmed the booster HOM coupler is OK
- Heater failed - Addressed by Linde in Dec. 2006, then again in Jan. 2007
- Will need to get many hours of operating experience before we have mastered this cryosystem.

1^{St} Cooldown – Towards 2 K



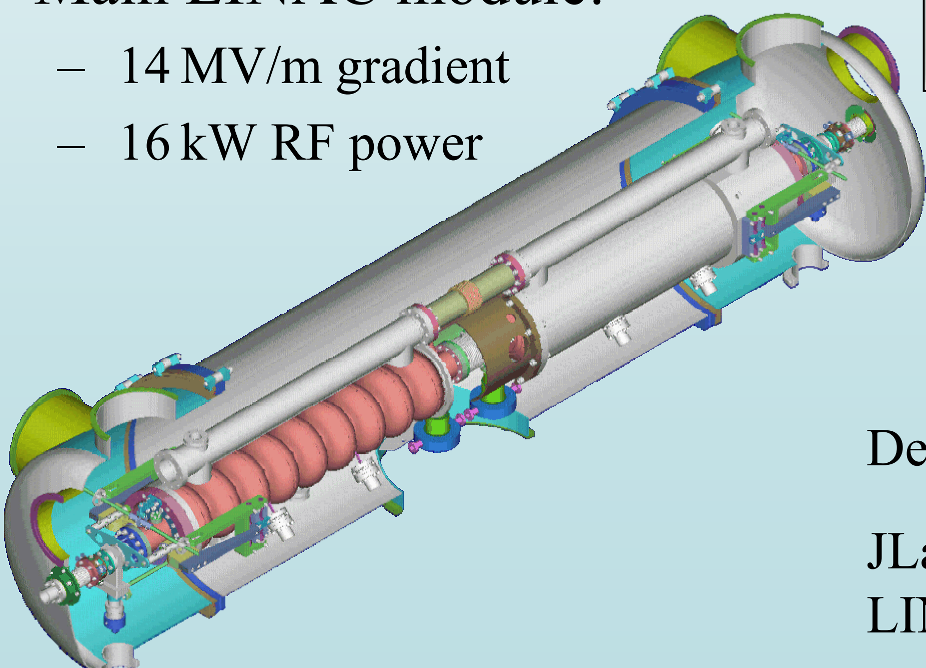
The 2 K Box





Superconducting RF Modules

- 2 × Stanford/Rossendorf cryomodules, one configured as the ***Booster*** and the other as the ***Main LINAC***.
- Booster module:
  - 4 MV/m gradient
  - 32 kW RF power
- Main LINAC module:
  - 14 MV/m gradient
  - 16 kW RF power

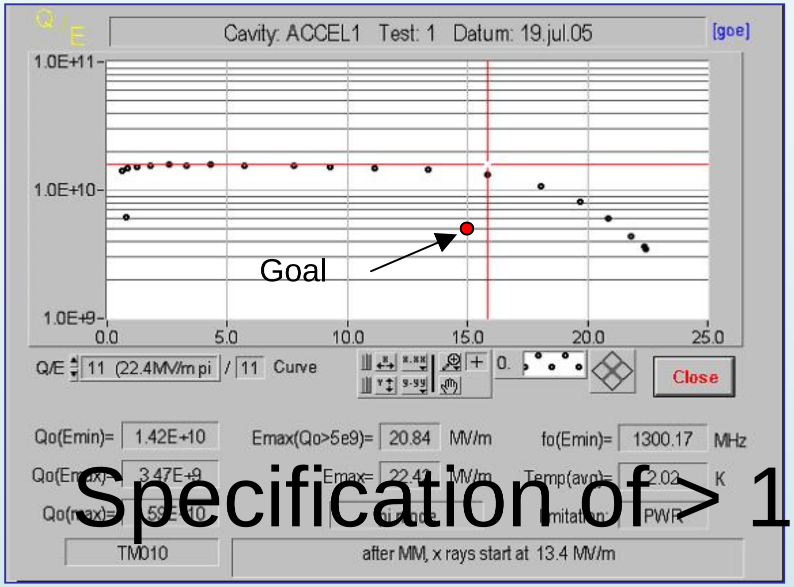


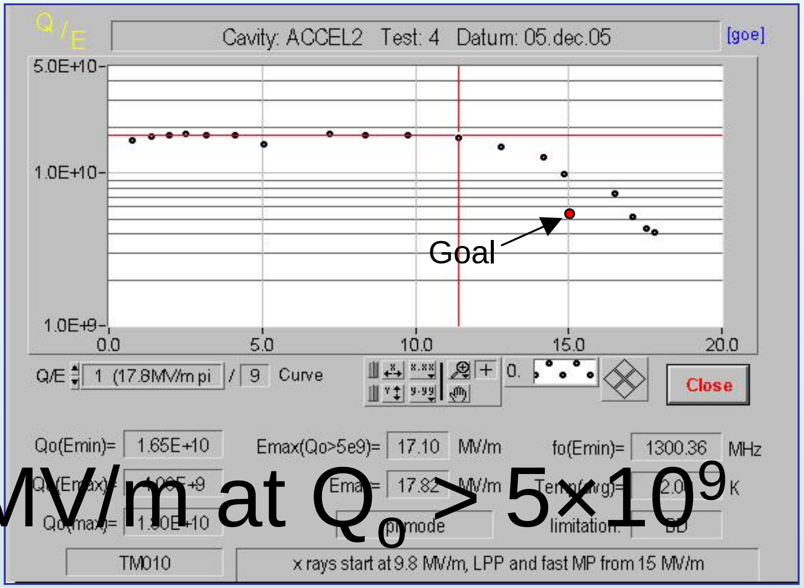
Delivery April/July 2006 (~7 months late)

JLab HOM coupler design adopted for the LINAC module

ERLP Cavity Test Results

1

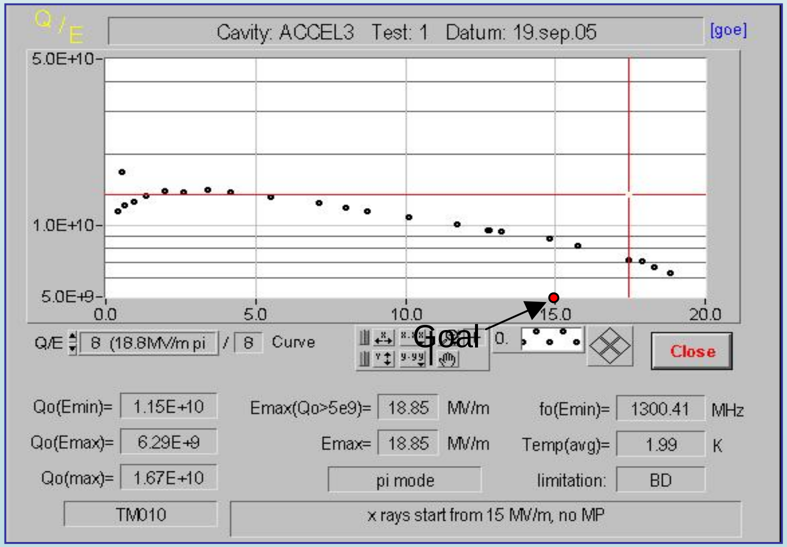


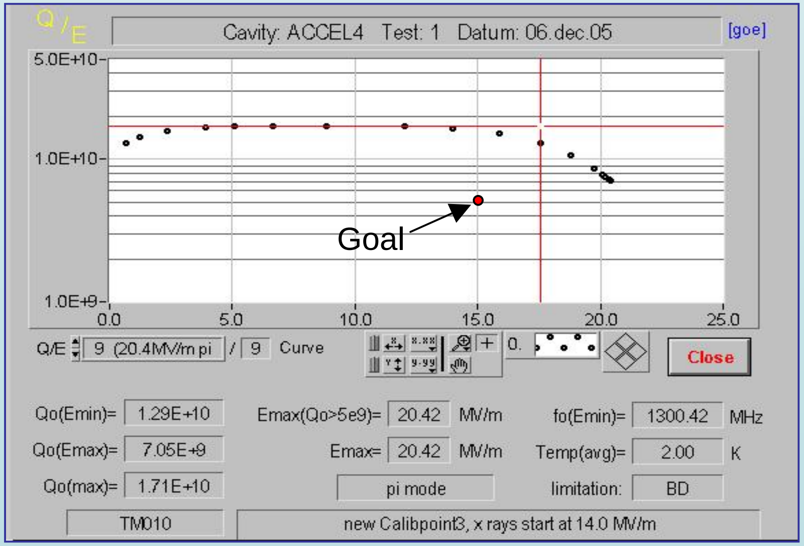


1

Specification of > 15 MV/m at $Q_o > 5\times10^9$

2



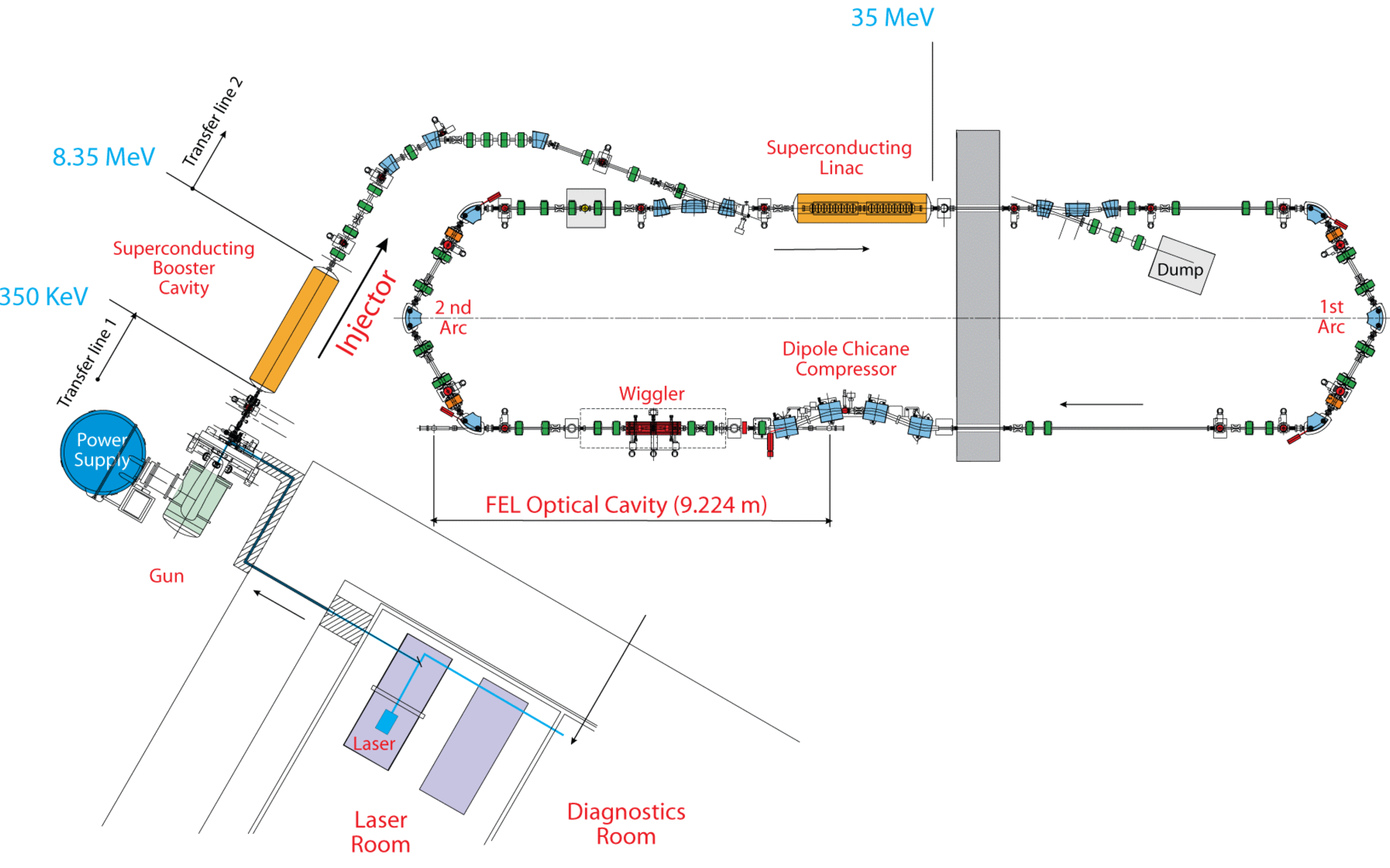


2

Booster Module

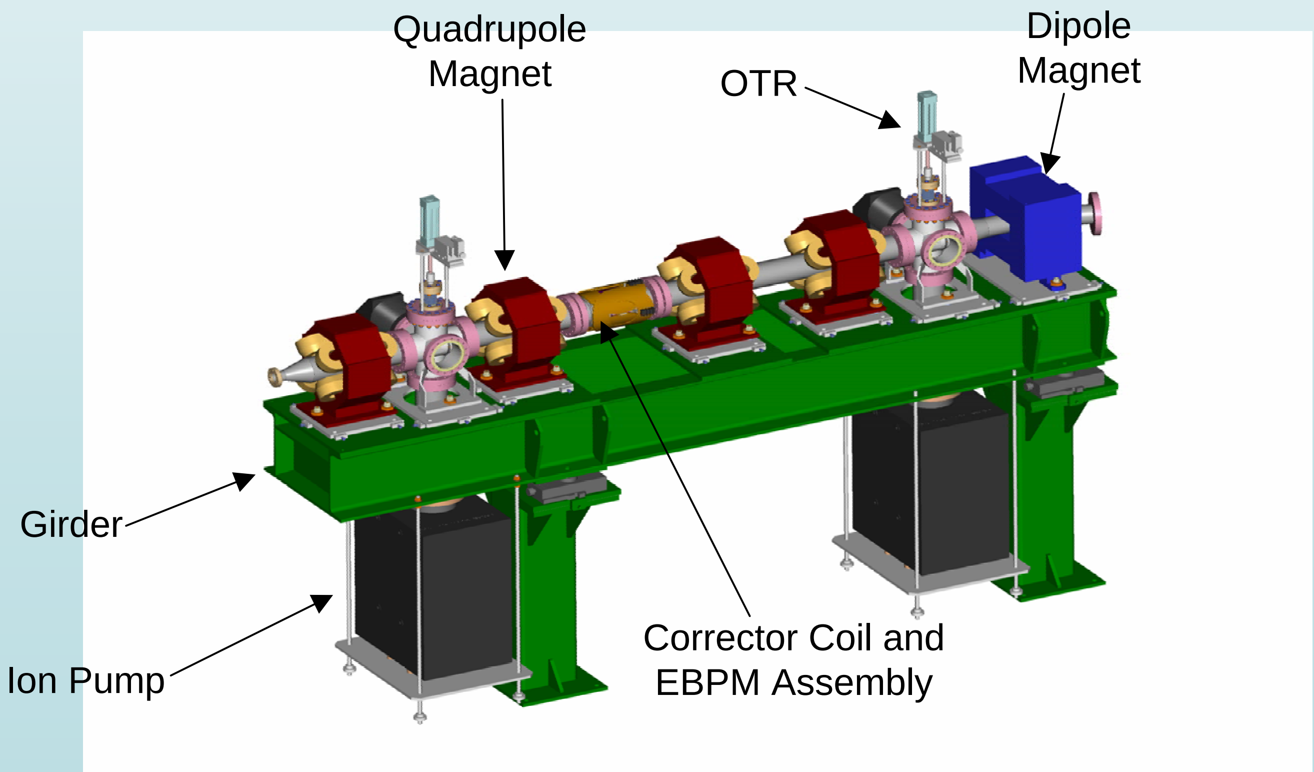
LINAC Module

Electron Beam Transport System Status



Electron Beam Transport System Status

- All but two modules are now fully-assembled and located in the Tower, waiting to be positioned and connected to form the ring BTS
- The last two share some components with the gun diagnostic line, or are being modified to add extra valves. They will be moved from the assembly area shortly



Ongoing work

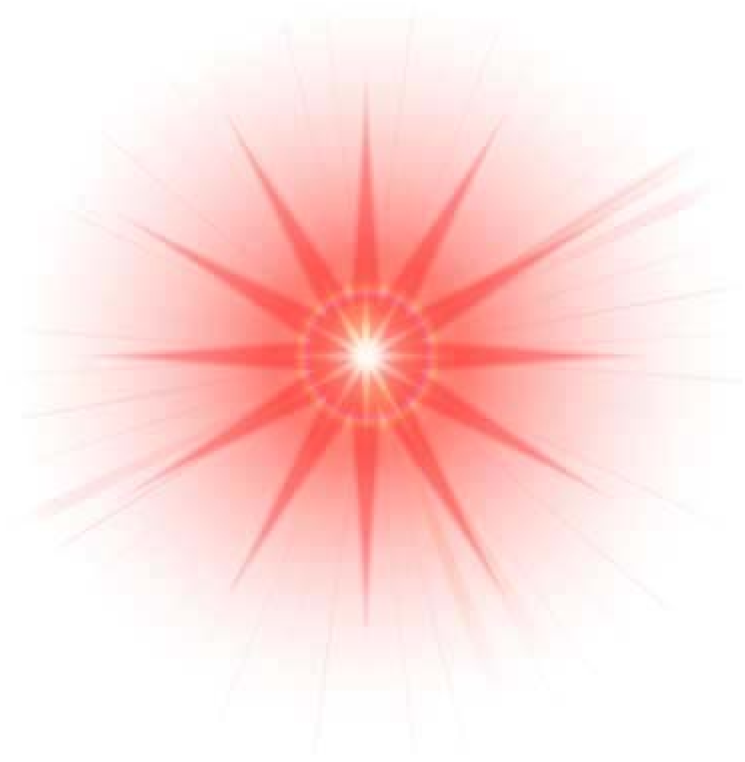
- Preparations for 2^{nd} phase of gun commissioning during January & February 2007
- Understanding and testing of the cryogenic system
- Installation and testing of all RF systems
- Commissioning of the booster and LINAC modules
- Final installation of the beam transport system
- Commissioning and acceptance of the terawatt laser

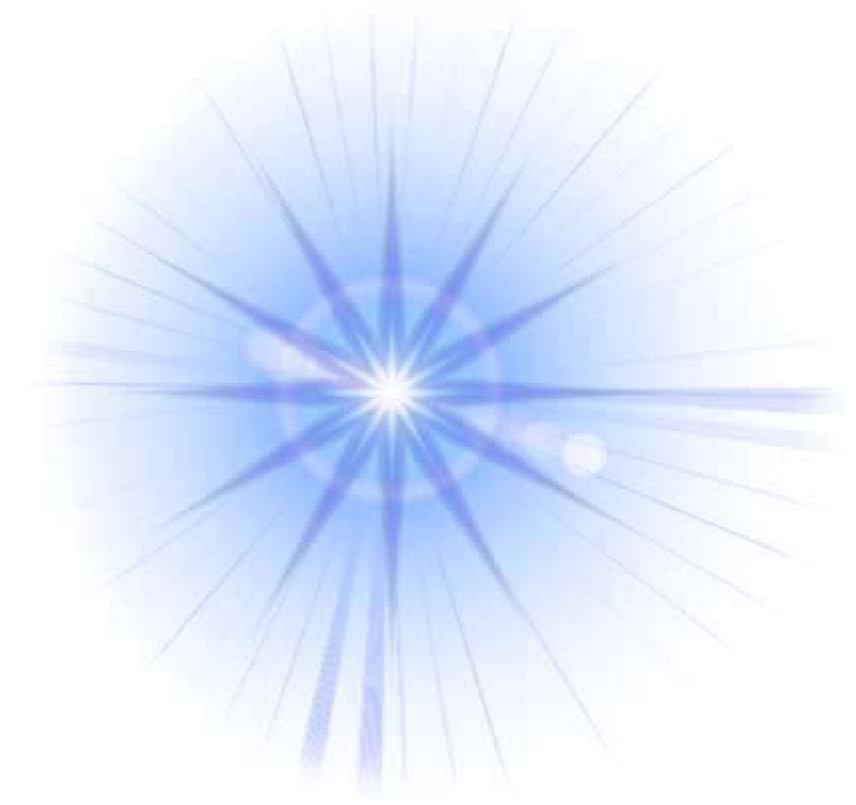
Future Plans

❖ Injector rebuild and bake to UHV	Xmas
❖ HV conditioning	early Jan
❖ Confirmation of LINAC gradient	early Jan
❖ Stable 2 K Cryo	end Jan
❖ Gun commissioning finished	end of Feb
❖ Full RF tests of modules	early March
❖ Beam through the booster	mid April
❖ Beam through the LINAC	end of June
❖ **Demonstrate energy recovery**	end Sept

- Install the wiggler
- Energy recovery from FEL-disrupted beam
- Generate photon output from the FEL

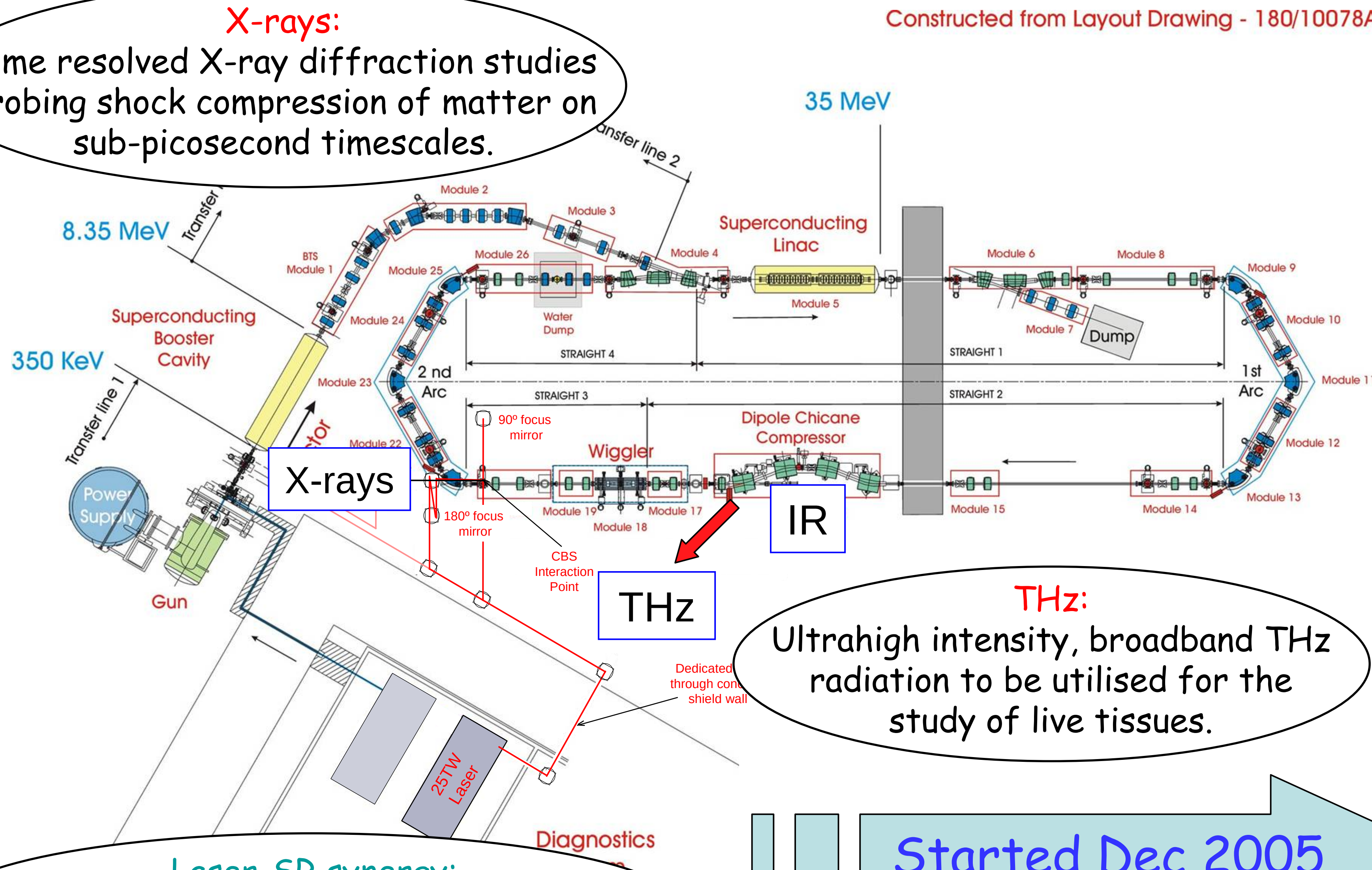
The Terawatt Laser for CBS & EO





ERLP Photon Science: North West Science Fund Award of £3m over 3 years

X-rays:
Time resolved X-ray diffraction studies probing shock compression of matter on sub-picosecond timescales.

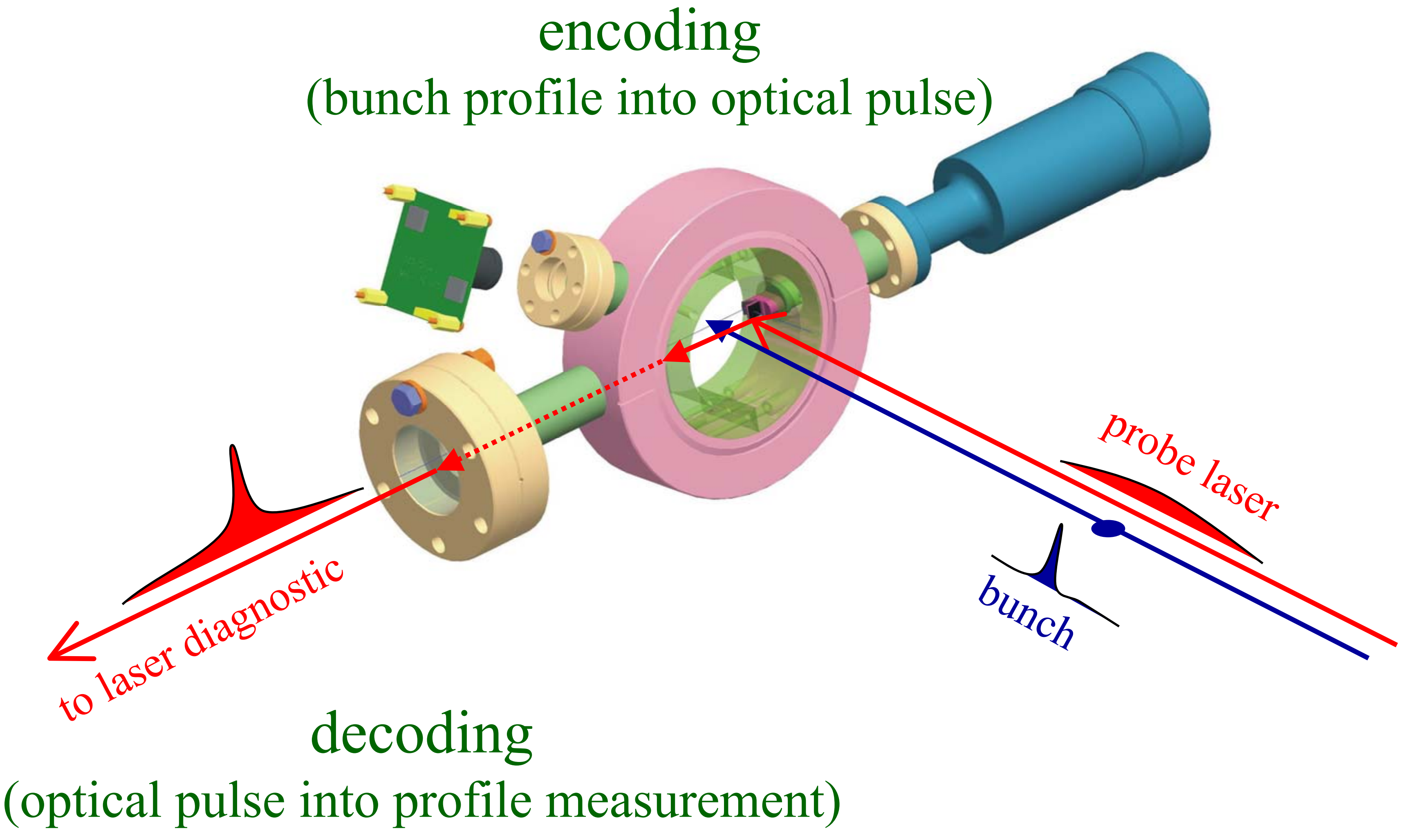


THz:
Ultrahigh intensity, broadband THz radiation to be utilised for the study of live tissues.

Laser-SR synergy:
Pump-probe expts with table-top laser and SR

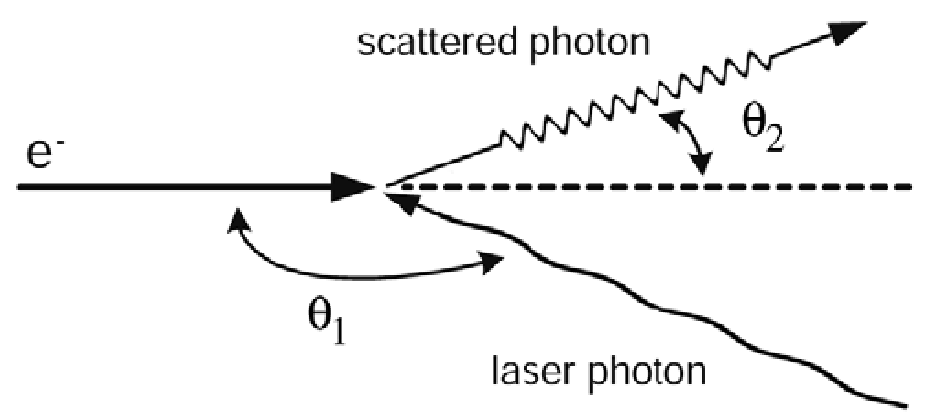
Started Dec 2005

Longitudinal Diagnostics: Electro-Optic Concept



Compton Back-Scattering ⇒ X-rays

$$E_\gamma = \frac{E_L(1-\beta\cos\theta_1)}{(1-\beta\cos\theta_2)+E_L[1-\cos(\theta_2-\theta_1)]/E_e}$$



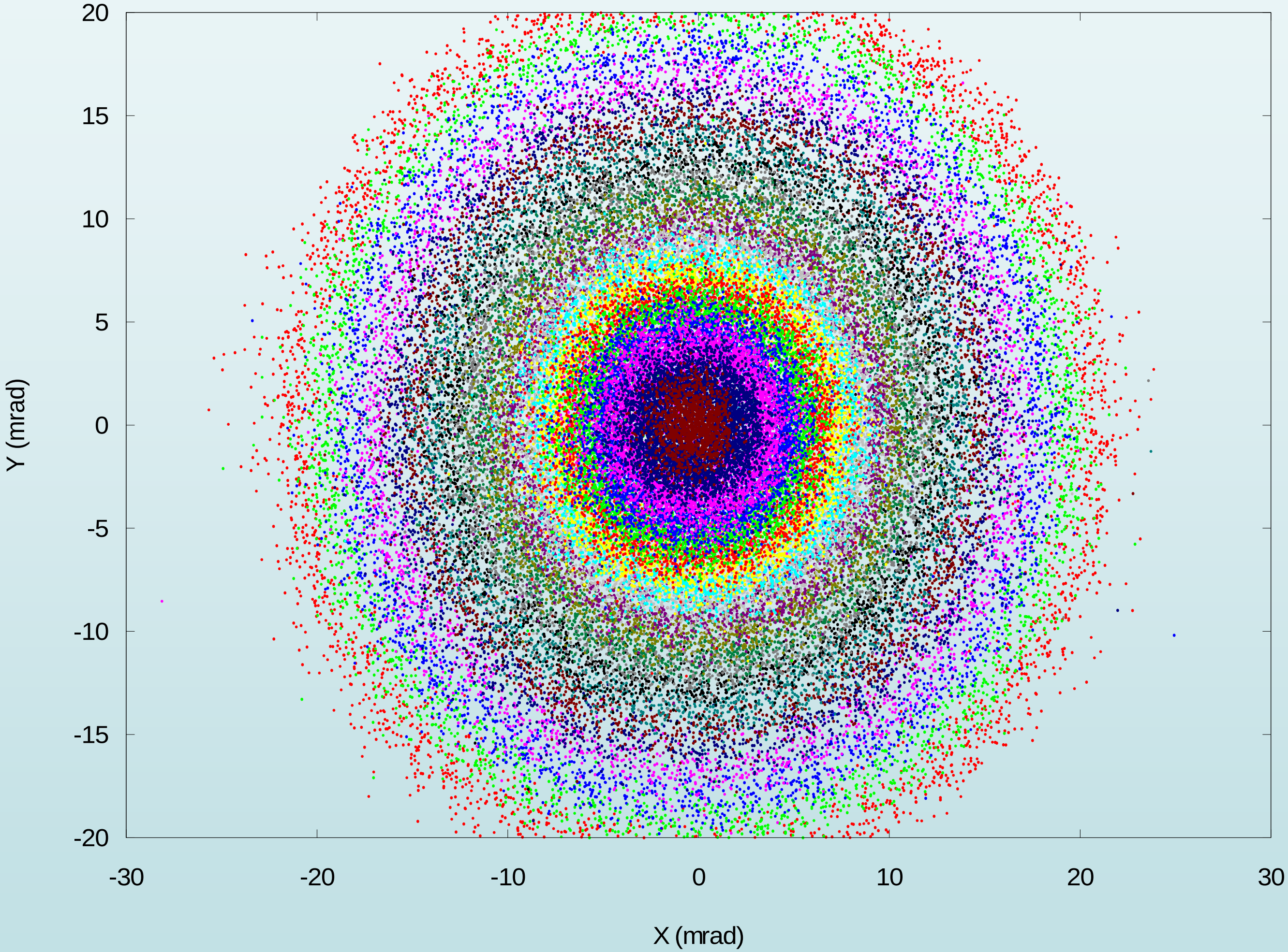
$\Theta_1=\pi$, $\Theta_2=0$

$$E_\gamma^{\mathrm{bs}} = \frac{E_L(1+\beta)E_e}{(1-\beta)E_e - 2E_L} \approx \frac{E_L(1+\beta)^2E_e}{E_e/\gamma^2} \approx 4\gamma^2 E_L$$

$\Theta_1=\pi/2$, $\Theta_2=0$

$$E_\gamma^{\mathrm{bs}} = 2\gamma^2 E_L$$

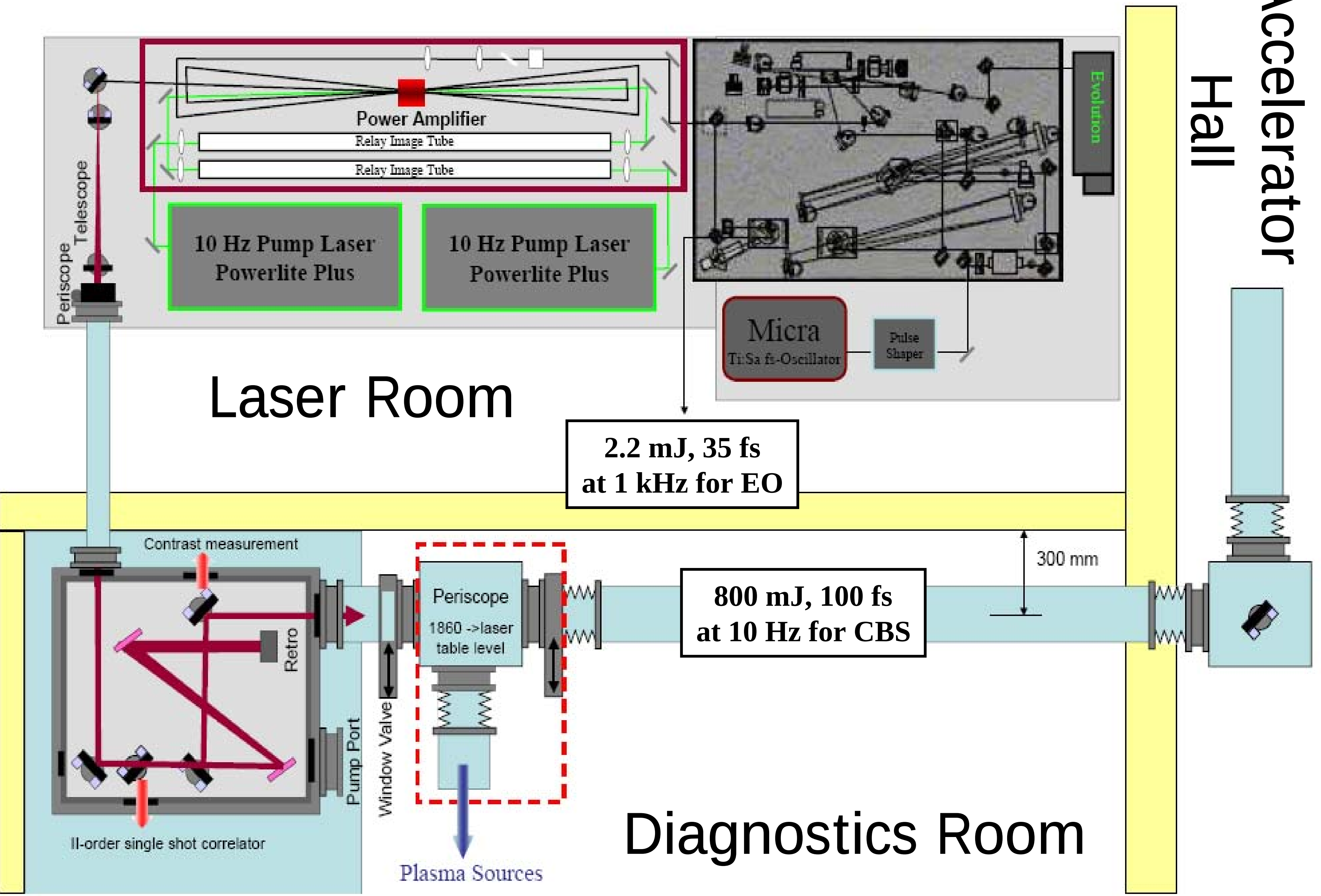
Back-Scattering Angular Distribution



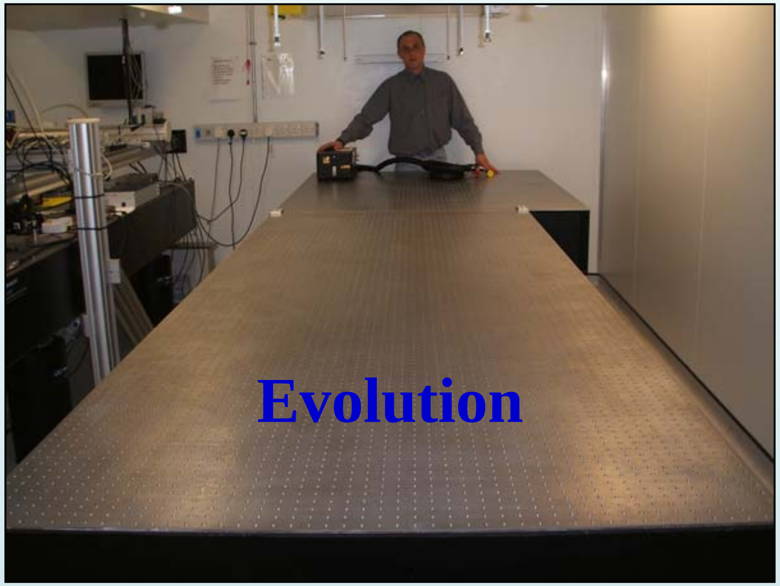
Each colour represents a 1 keV energy band, with the 20-21 keV band on outside, and the 30-31 keV band at the centre.

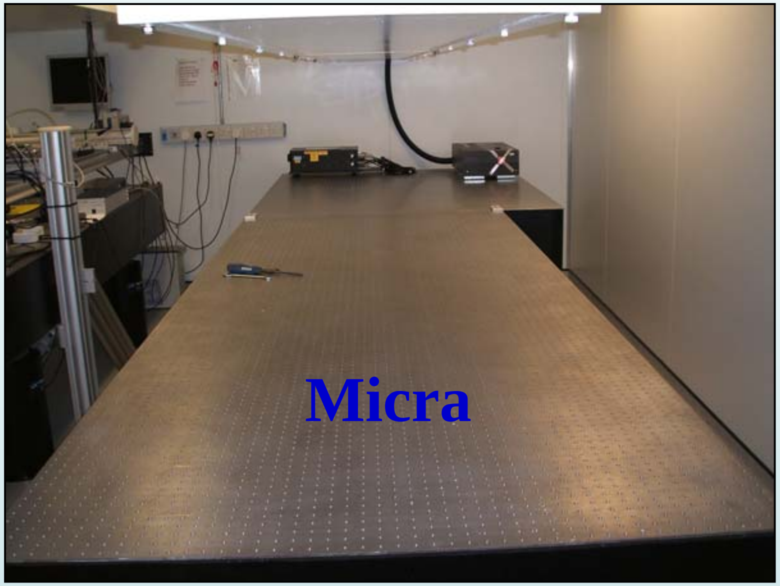
What we expect to get from CBS

Laser Power: 8 TW @ 10 Hz	Head-on Collision	Side or Top Collision
X-ray Energy	$\approx$ 30 keV	$\approx$ 15 keV
X-rays	15×10^6	3.5 (top) to 8 (side) $\times10^6$
X-ray Pulse	~ Electron Bunch Length	~ Laser Pulse Length
X-ray Source Size	50 μm × 20 μm	10 μm × 20 μm or 10 μm × 50 μm

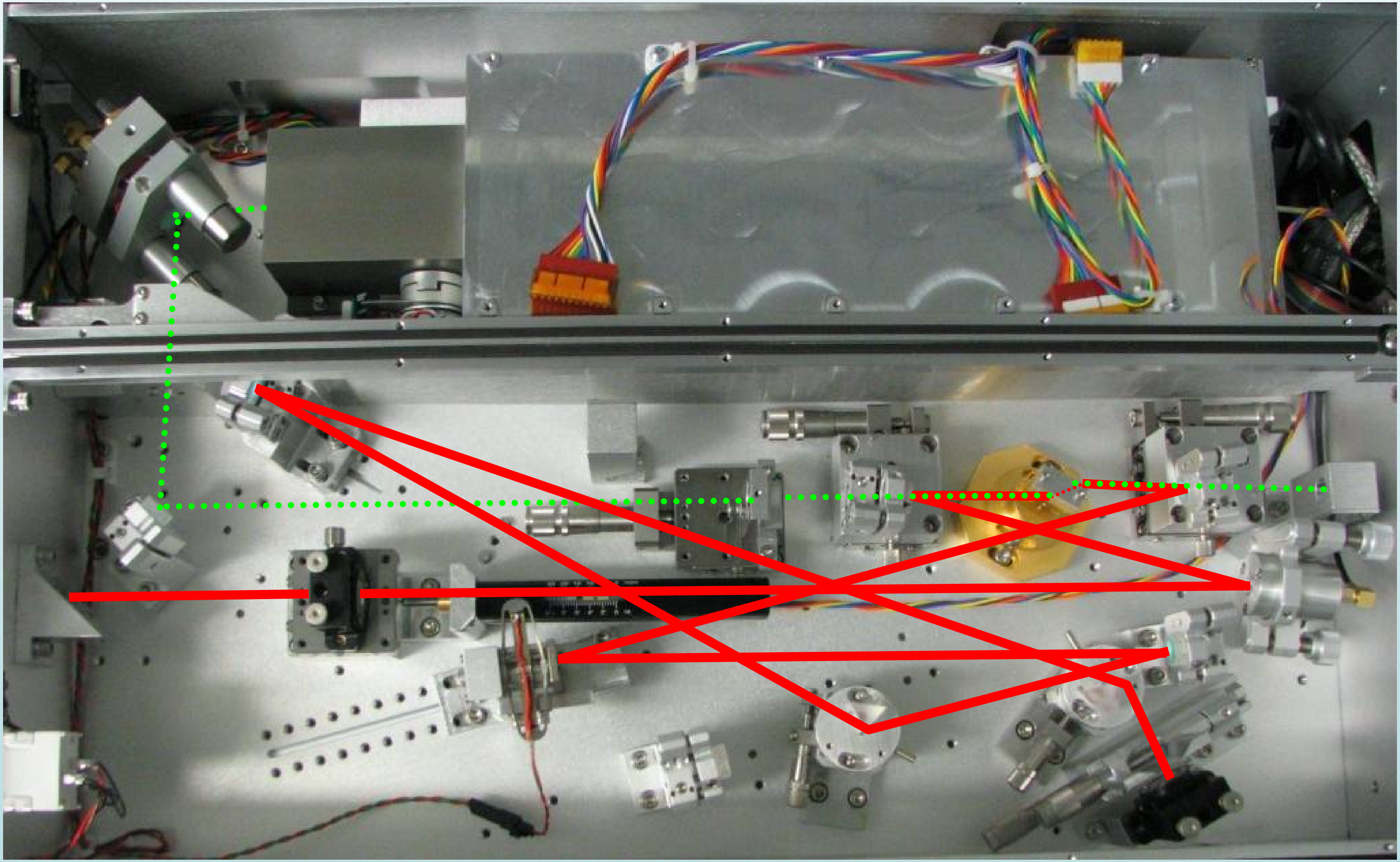

Accelerator Hall
Power Amplifier
Relay Image Tube
Relay Image Tube
10 Hz Pump Laser Powerlite Plus
10 Hz Pump Laser Powerlite Plus
Evolution
Periscope
Telescope
Micra
Ti:Sa fs-Oscillator
Pulse Shaper
Laser Room
2.2 mJ, 35 fs
at 1 kHz for EO
Contrast measurement
Retro
Pump Port
Window Valve
Periscope
1860 ->laser table level
300 mm
800 mJ, 100 fs
at 10 Hz for CBS
II-order single shot correlator
Plasma Sources
Diagnostics Room

Installation of the TW Laser

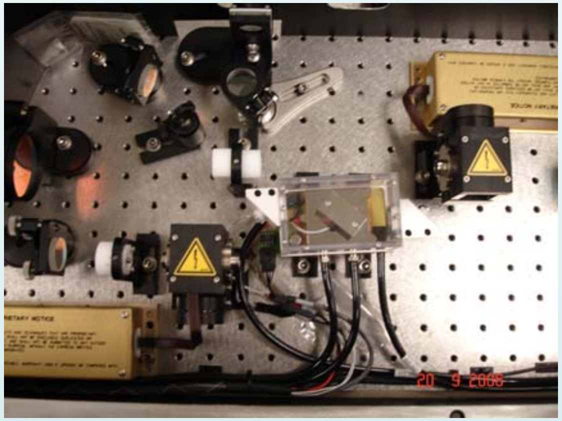


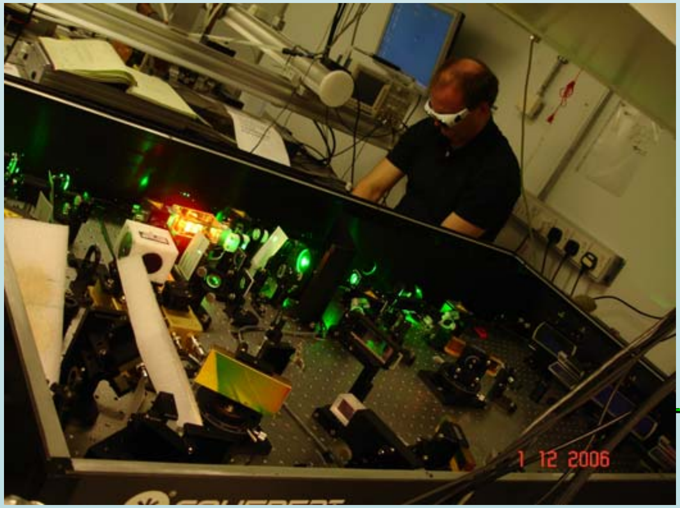


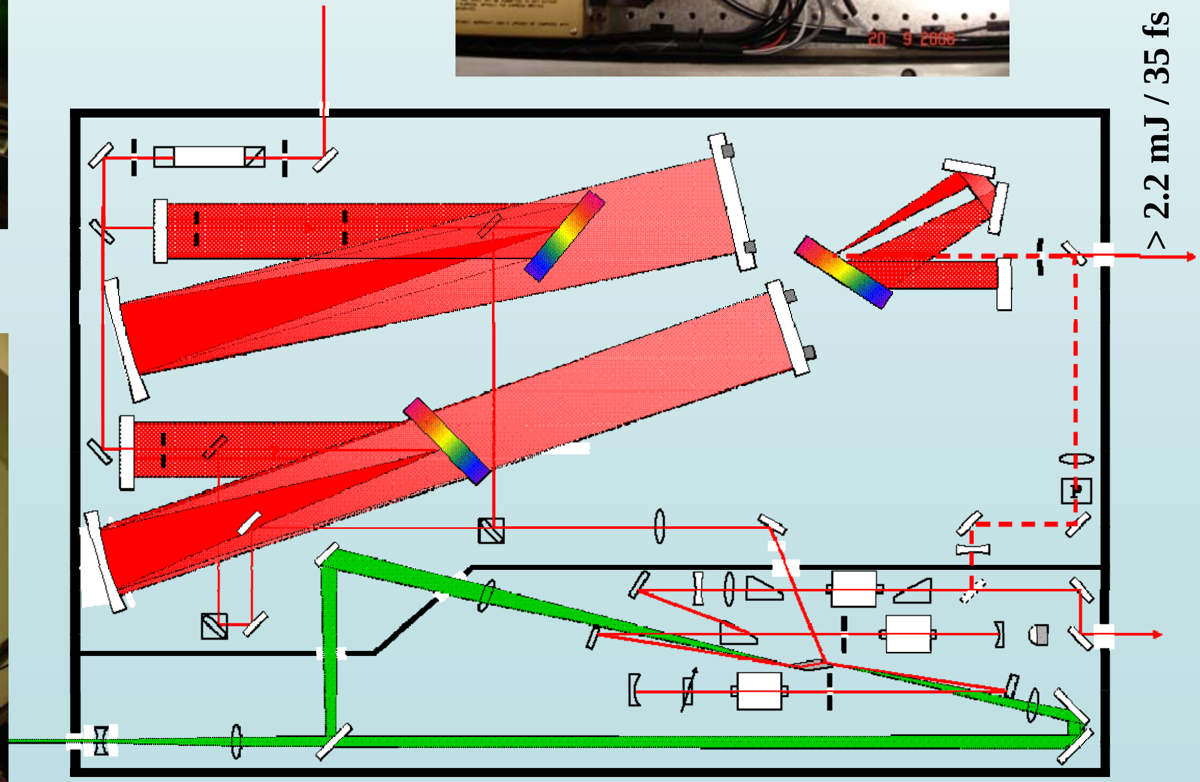
The *Micra* Master-Oscillator



The *Legend* Regenerative Amplifier

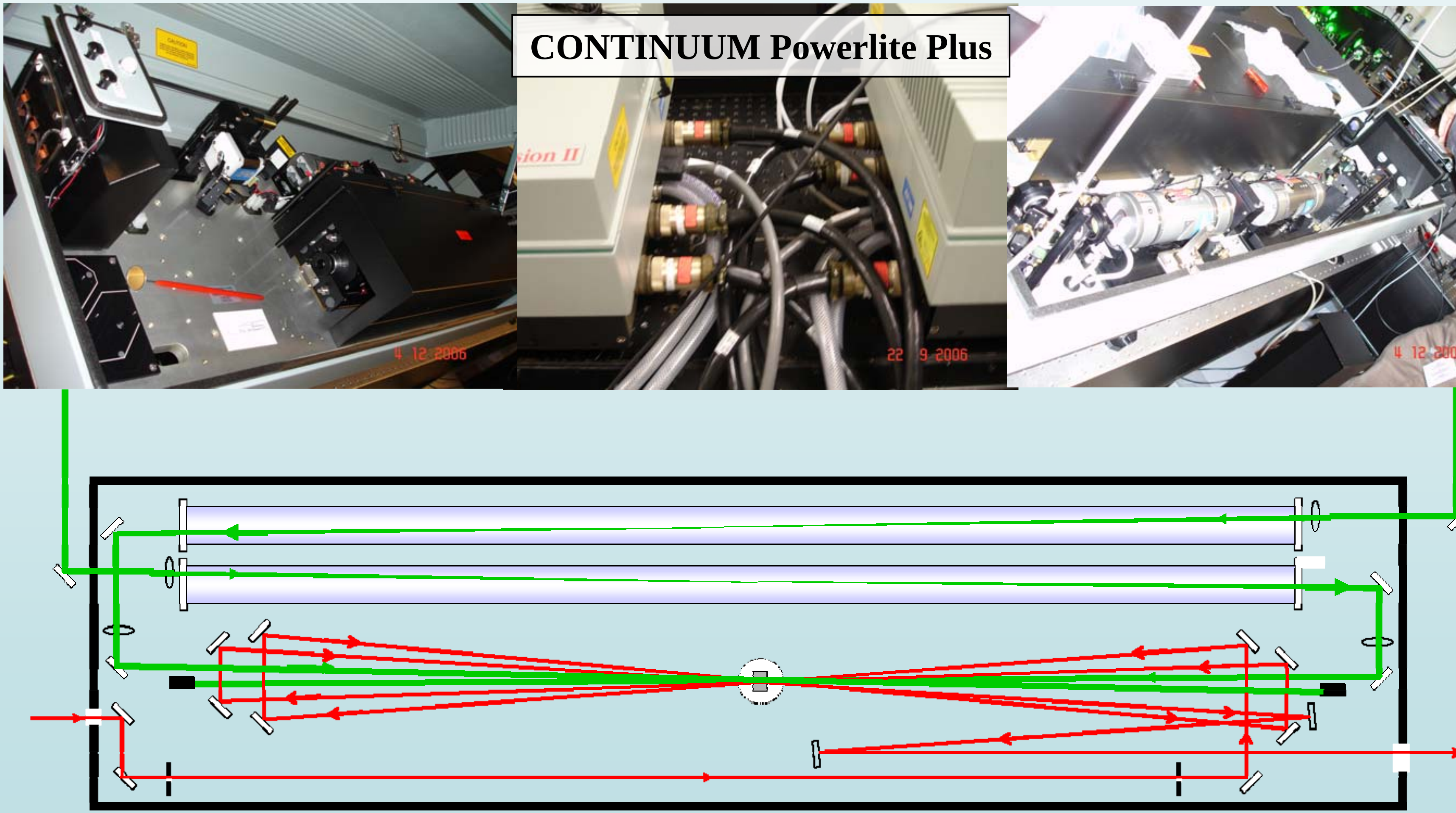






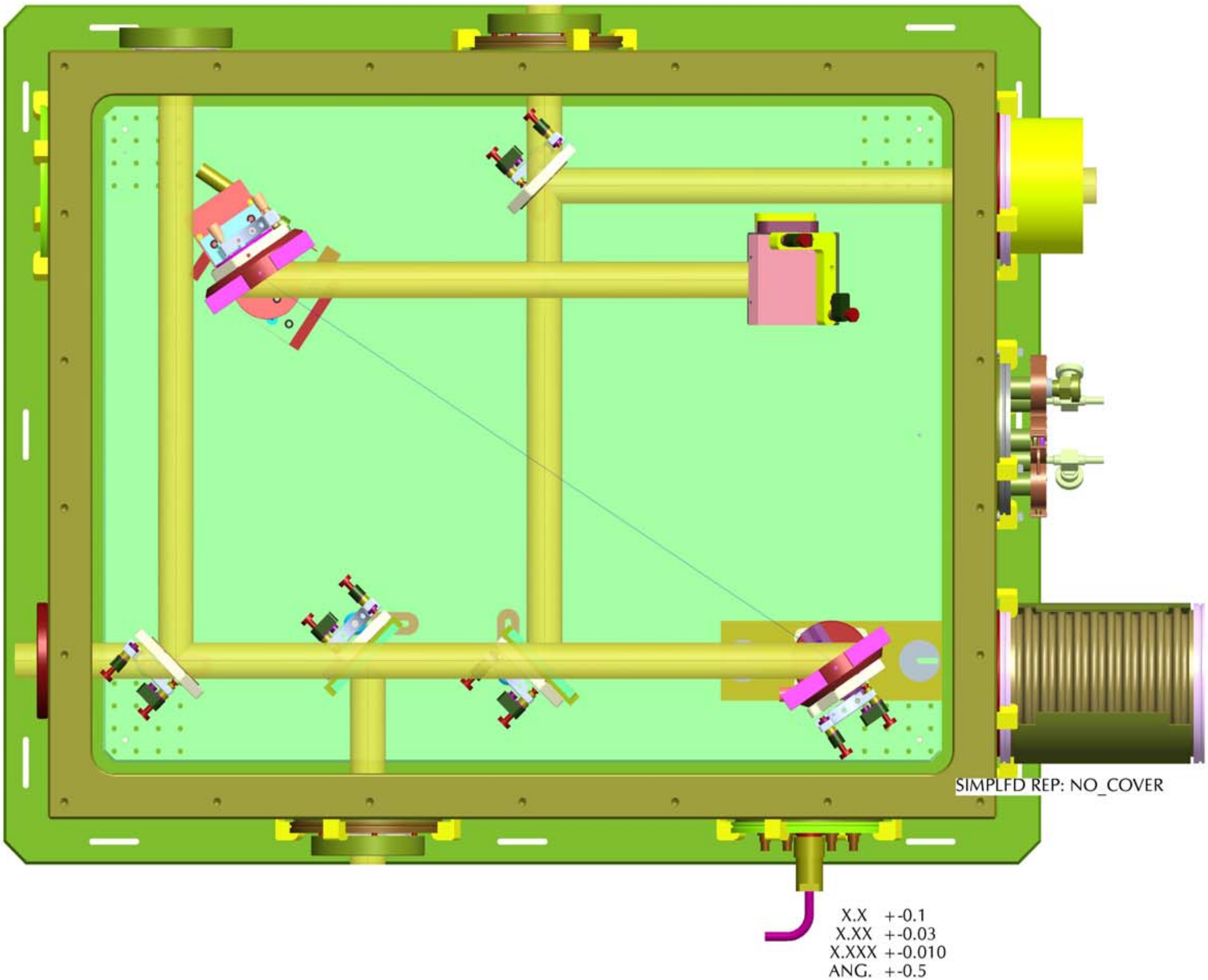
> 2.2 mJ / 35 fs @ 1 kHz

The Multi-Pass Power Amplifier

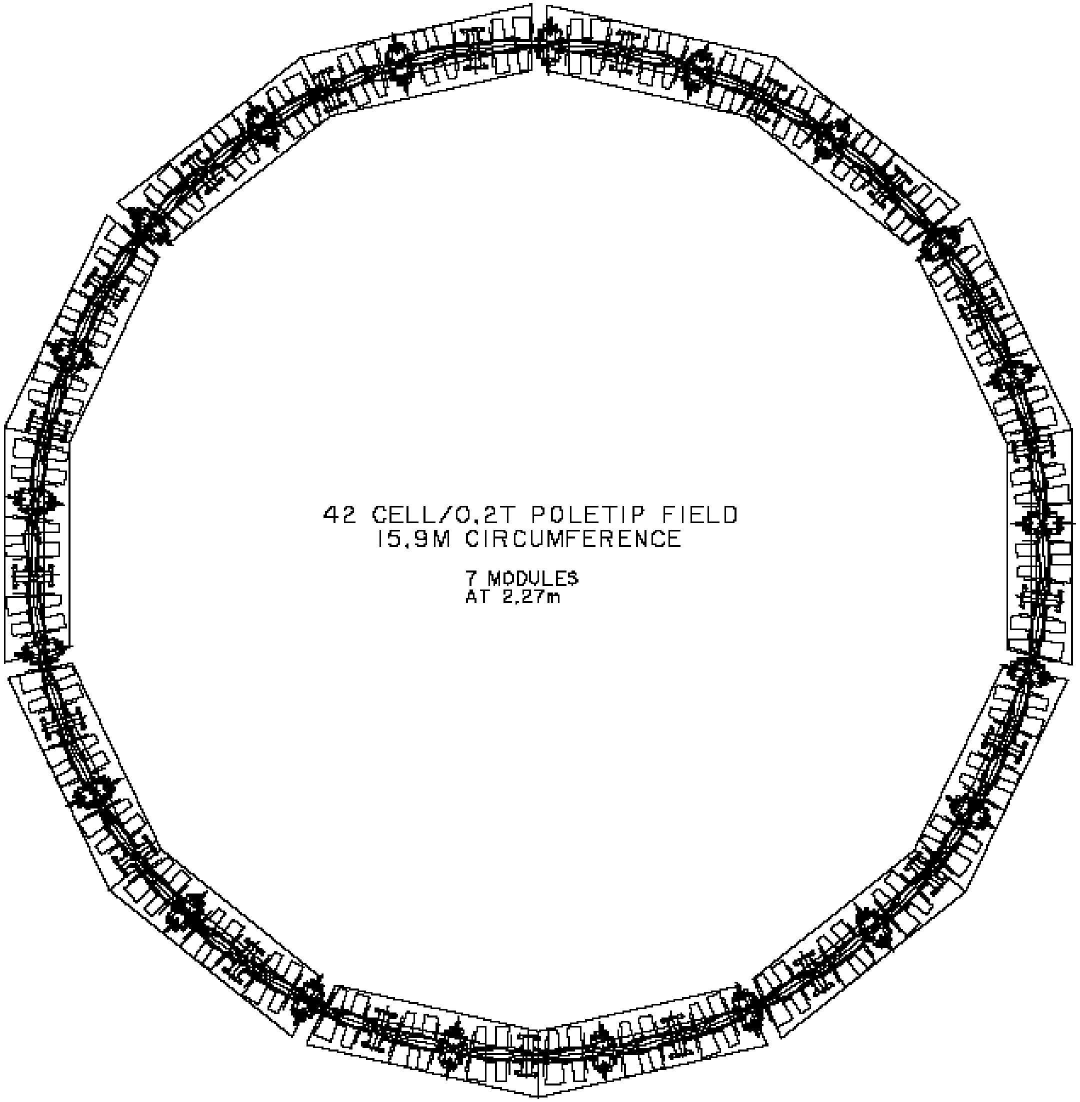


> 1.5 J / 200 ps @ 10 Hz

The *Compressor*: Chirped-Pulse Amplifier



The EMMA Project



BASROC : **B**ritish **A**ccelerator **S**cience and **R**adiation **O**ncology **C**onsortium

- The long-term aim of BASROC is to build a complete hadron th[illegible]cility using **Non-Scaling Fixed-Field Alternating Gradient** acce[illegible]echnology (**NS-FFAG**), combining the best features of cyclotron a[illegible]hrotron accelerators
- An FFAG combines the *intensity* and *ease-o*[illegible]yclotrons .... coupled with the benefits of synchrotrons, speci[illegible]*m control* and the *ability* to accelerate proton and heavy ion bea[illegible]*ious energies*
- **EMMA:** The **E**lectron **M**ode[illegible]y **A**pplications will use the ERLP as an injector at 10 MeV, acce[illegible]lectrons to 20 MeV. The goal is to learn how to design NS-FFAG[illegible]ous applications, including hadron therapy
- **PAMELA:** T[illegible]le **A**ccelerator for **ME**dica**L** **A**pplications will be a 70 to 100 MeV[illegible]S-FFAG, itself a prototype to demonstrate the potential use of NS[illegible] in hadron therapy, thus strengthening the case for hadron therapy
- [illegible]g to a **complete facility** for the treatment of patients using hadron beams

Awarded £6.9m over 3½ years to design and build EMMA

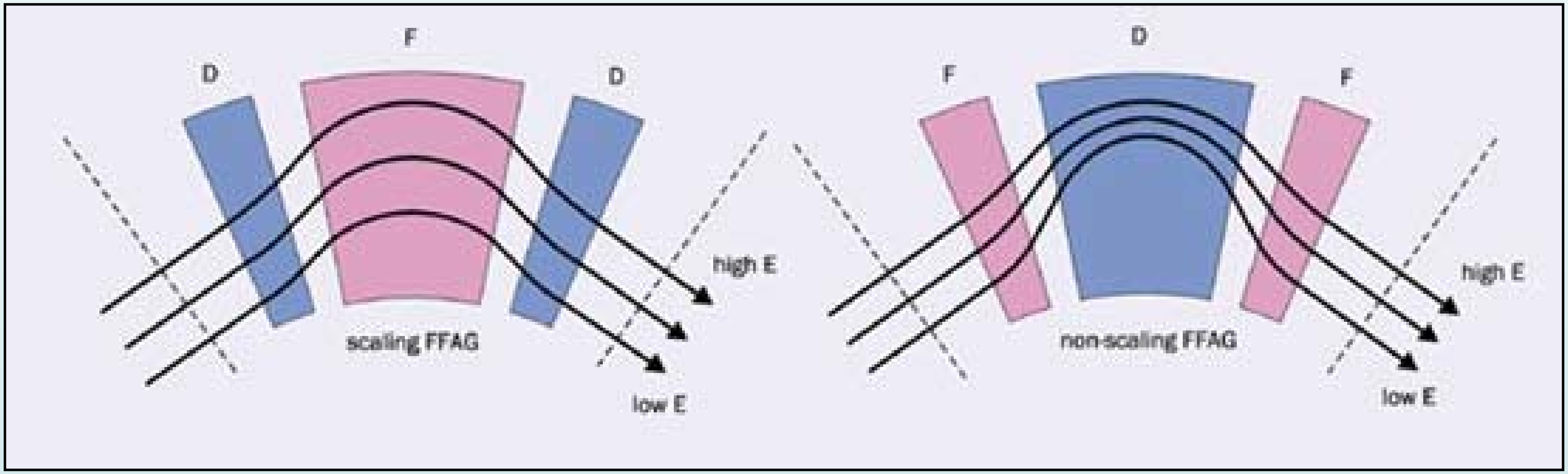
(Scaling) FFAG Technology

- Scaling Fixed-Field Alternating Gradient (FFAG) accelerators were invented in the 1950's. Machines of this type have been built and successfully tested in Japan, Russia and the US
- Fixed magnet fields enable FFAGs to be cycled faster than synchrotrons, limited only by the characteristics of the RF. This simplifies power supplies and reduces costs, eases operation, and yields rapid acceleration
- They have large beam acceptance, allowing high intensities with low beam loss, and are physically compact making them easier to locate in industrial or clinical environments
- FFAGs have the potential to achieve a ***major development in accelerator technology*** by replacing cyclotrons and synchrotrons in some applications, allowing major developments in new areas of technology

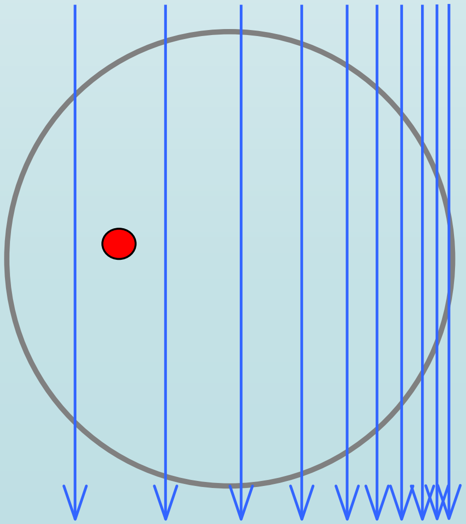
NS-FFAG Technology

- The (non-scaling) NS-FFAG was invented in 1999, and differs from a scaling FFAG in two keys respects:
  - Linear variation in the magnet field causes a parabolic variation in orbit length with energy, thus greatly compressing the range of orbit radii and reducing the magnet aperture
  - Smaller and simpler magnets reduce cost, and yield a more-compact machine than an equivalent scaling FFAG
- It is possible to use a fixed RF frequency, thus simplifying the RF system
- Magnet fields do not scale with energy, so tunes will vary and many transverse resonance conditions will be crossed during acceleration
- This is a new acceleration mode offering many new challenges, and ***no such machine has been built anywhere else***

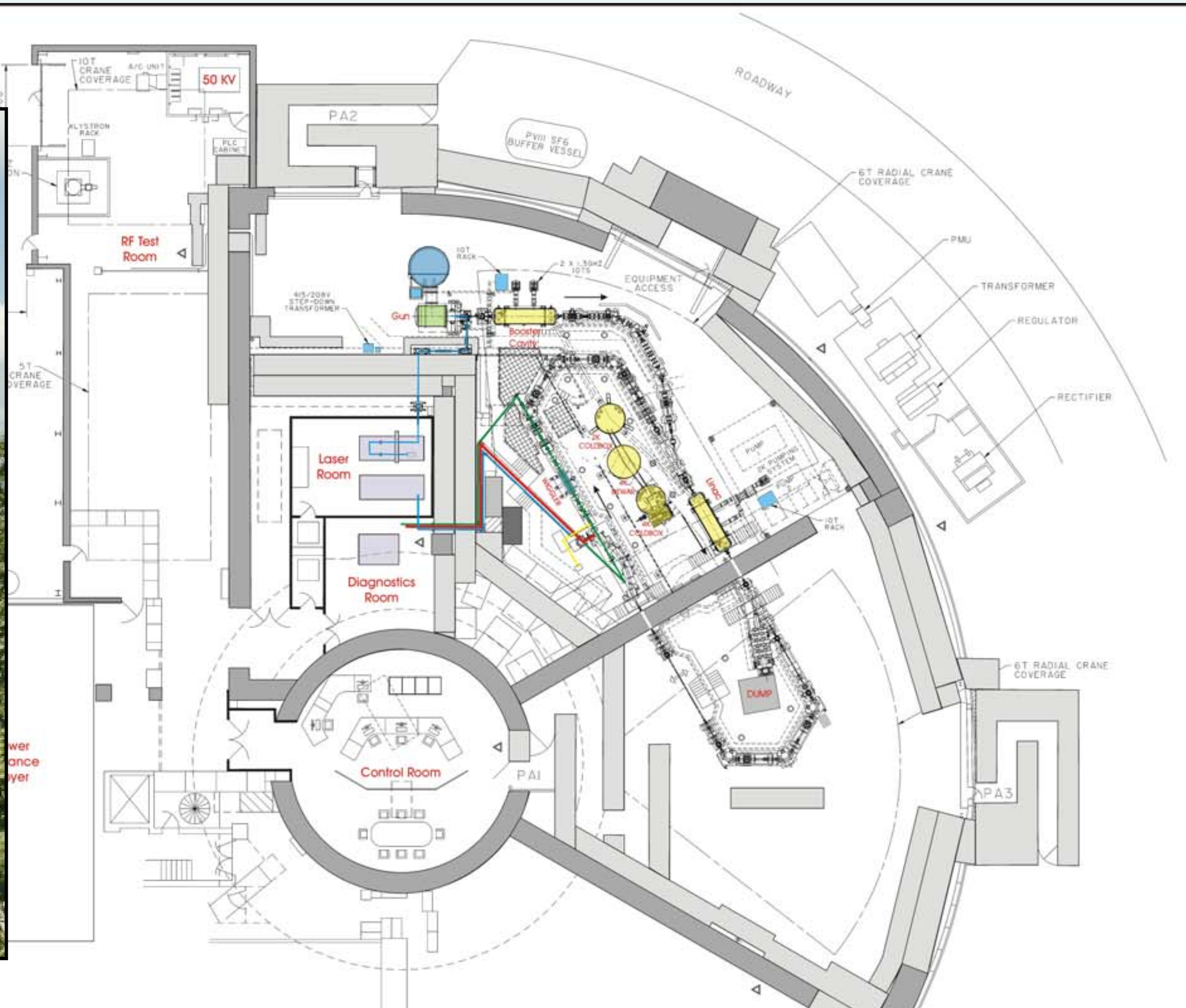
To Scale, or *Not* to Scale ?



- The ***scaling*** machine has a constant orbit shape, whilst the ***non-scaling*** machine clearly does not
- If the tune changes rapidly, the resonances encountered during acceleration do not have time to destroy the beam
- Rapid acceleration: Big turn-to-turn energy variation
- This is plausible, but needs verifying



ERLP Layout in the NSF Tower

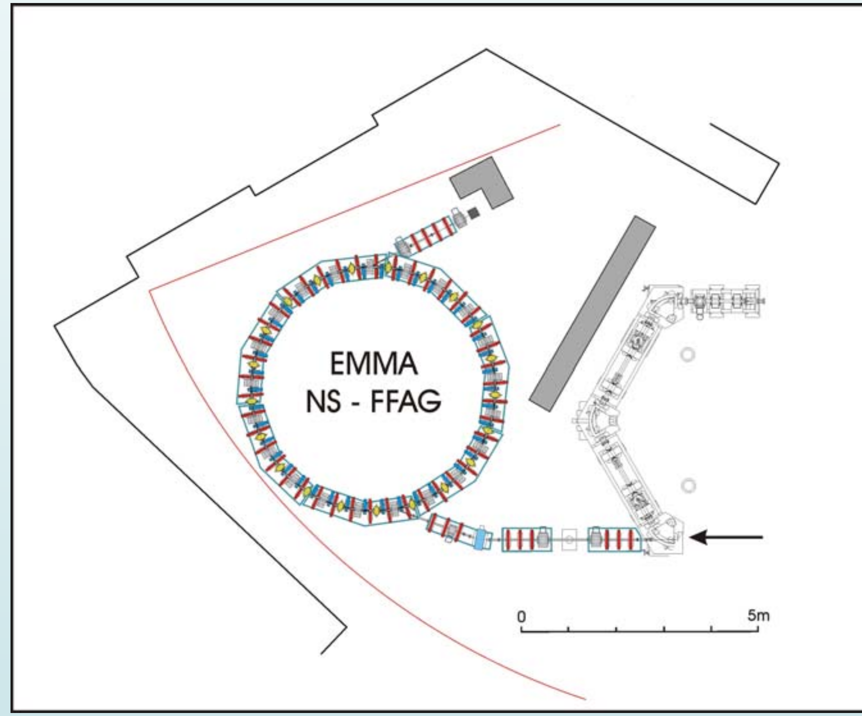


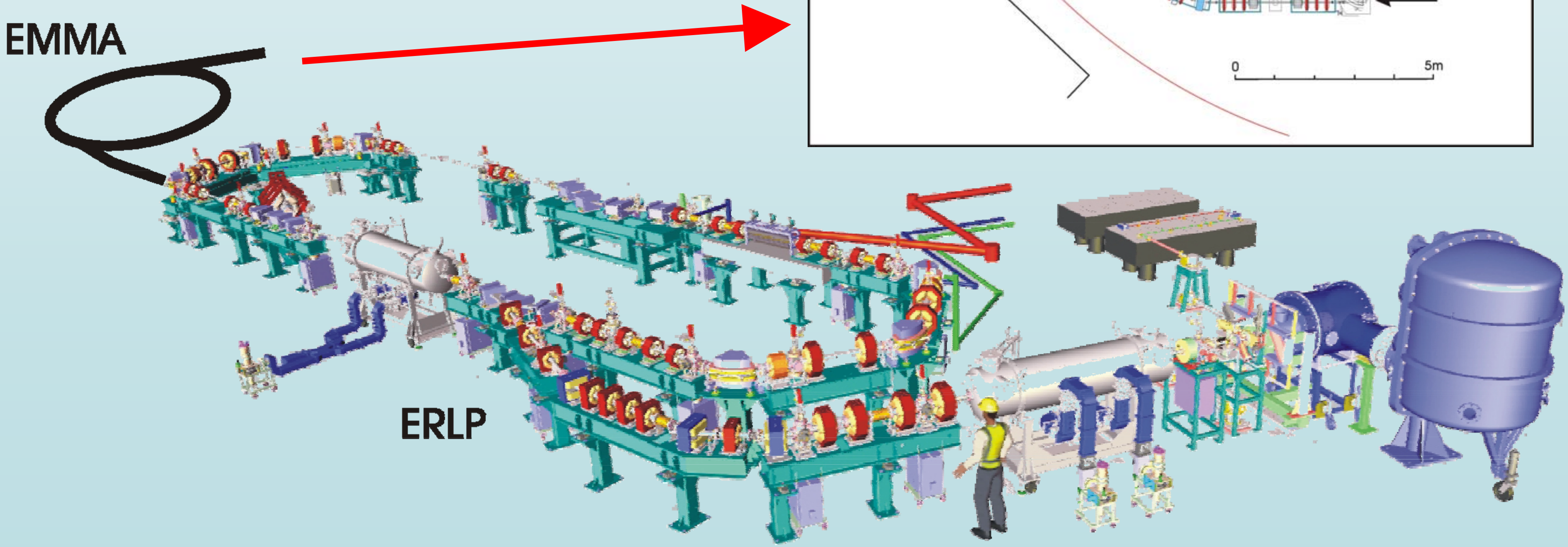
Energy Recovery Linac Project Building Layout

Constructed from Layout Drawing - 180/10080 F

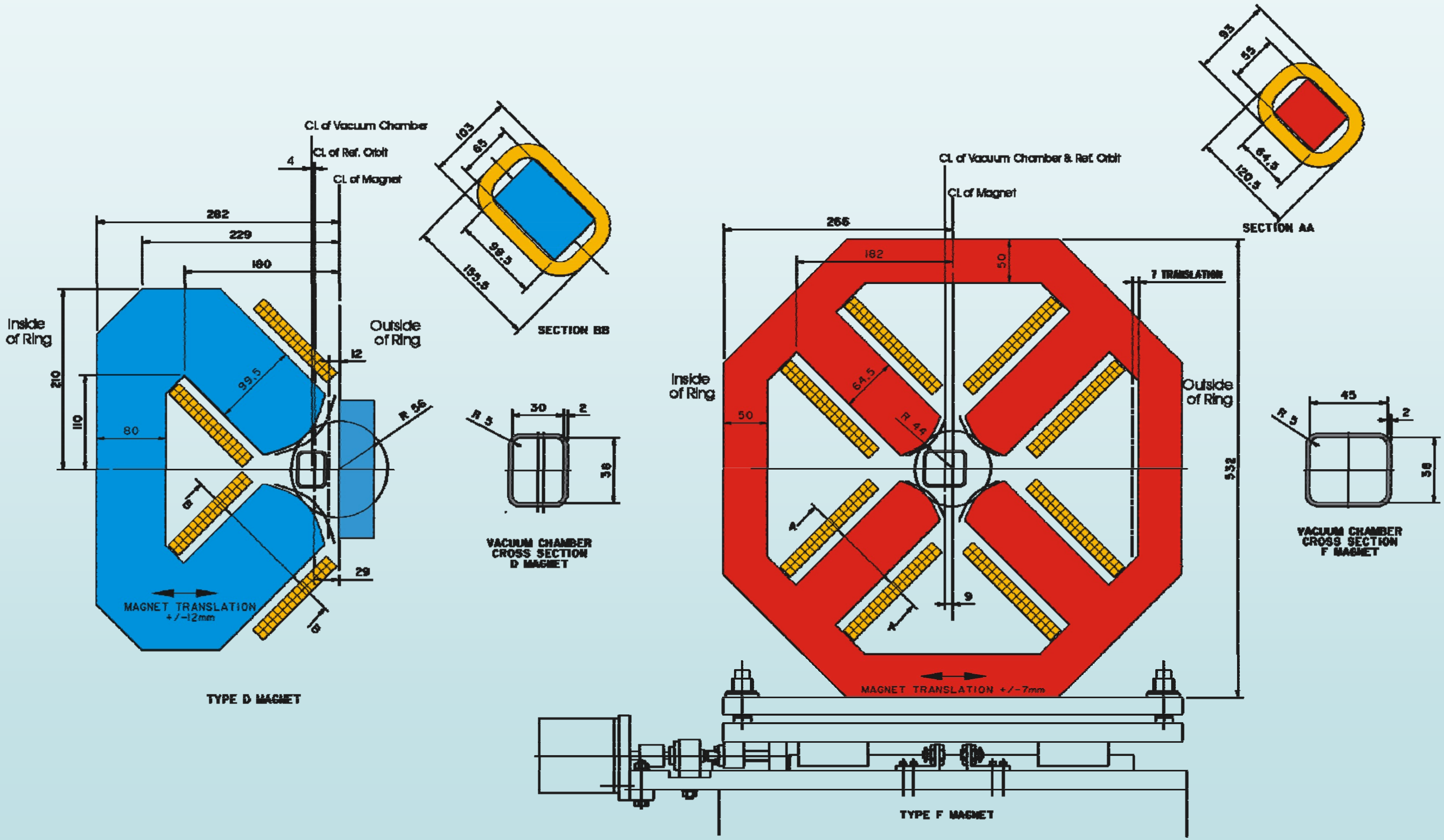
EMMA on ERLP

Parameter	Design Value
Energy range	10.5 to 20.5 MeV
Number of cells	42
Lattice	Doublet
Cell length	393.33 mm
Circumference	16.519 m
Height from ground	1.4 m
Repetition rate	1 Hz
Orbit swing	3 cm

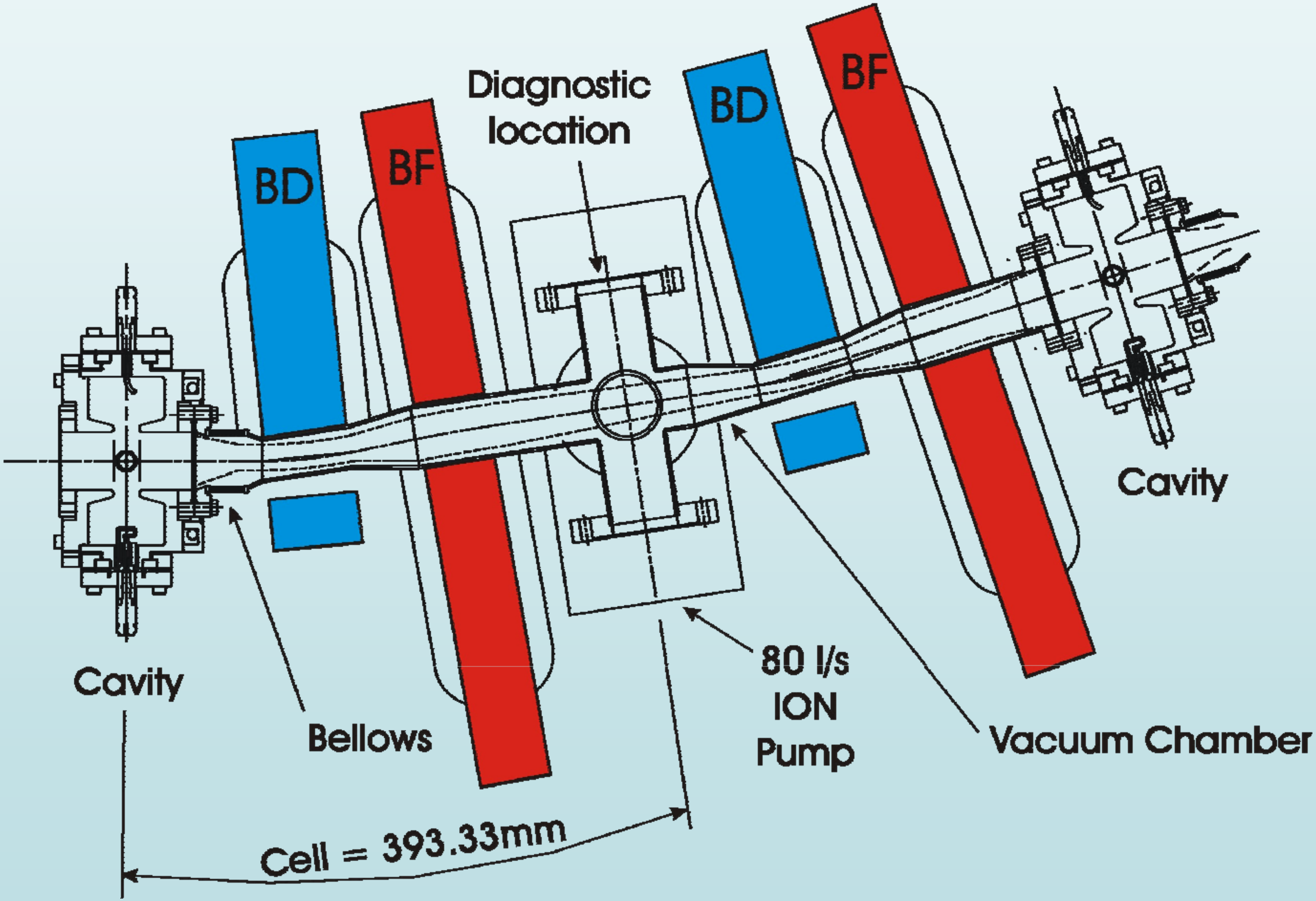




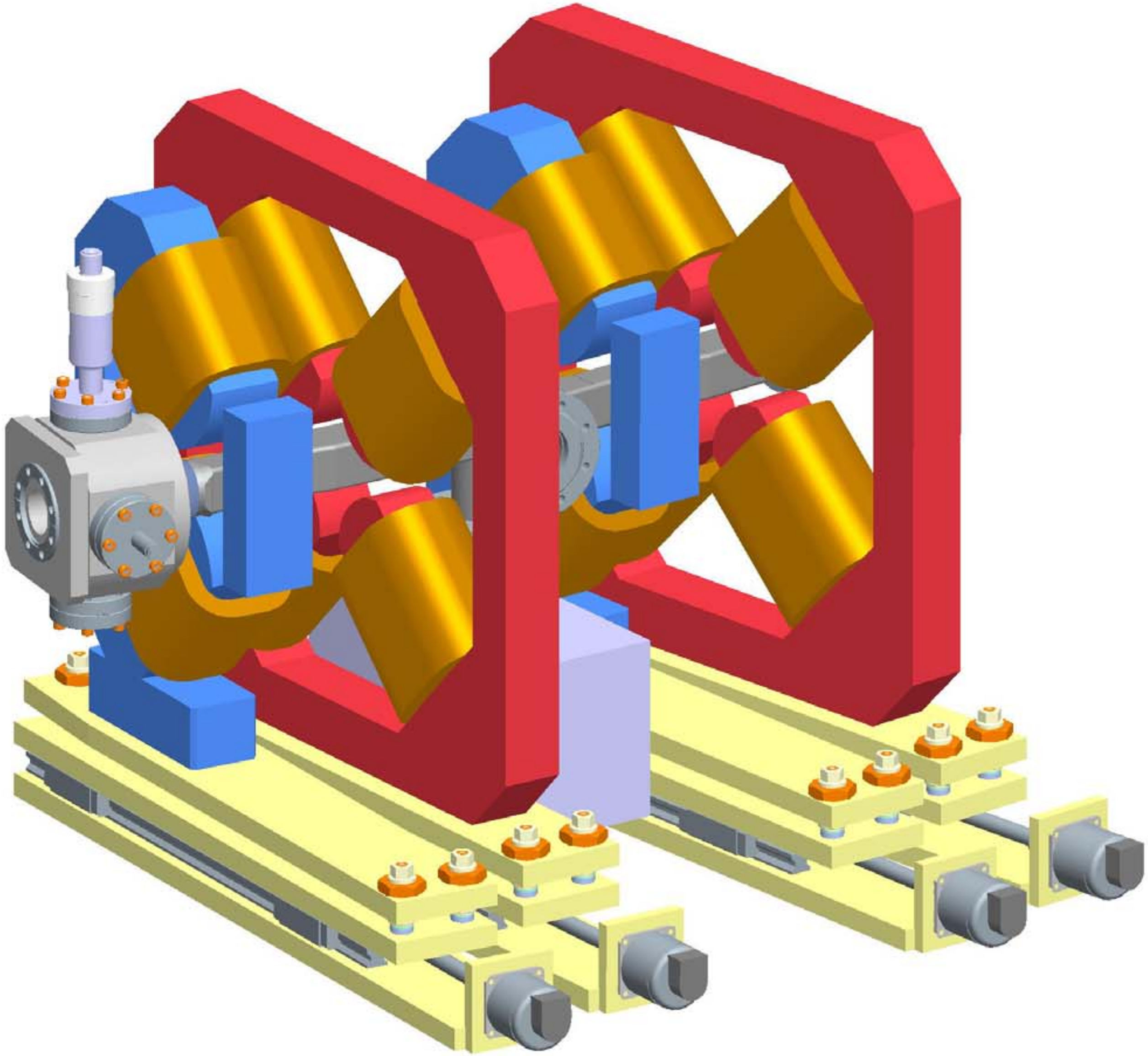
EMMA Magnet Sections



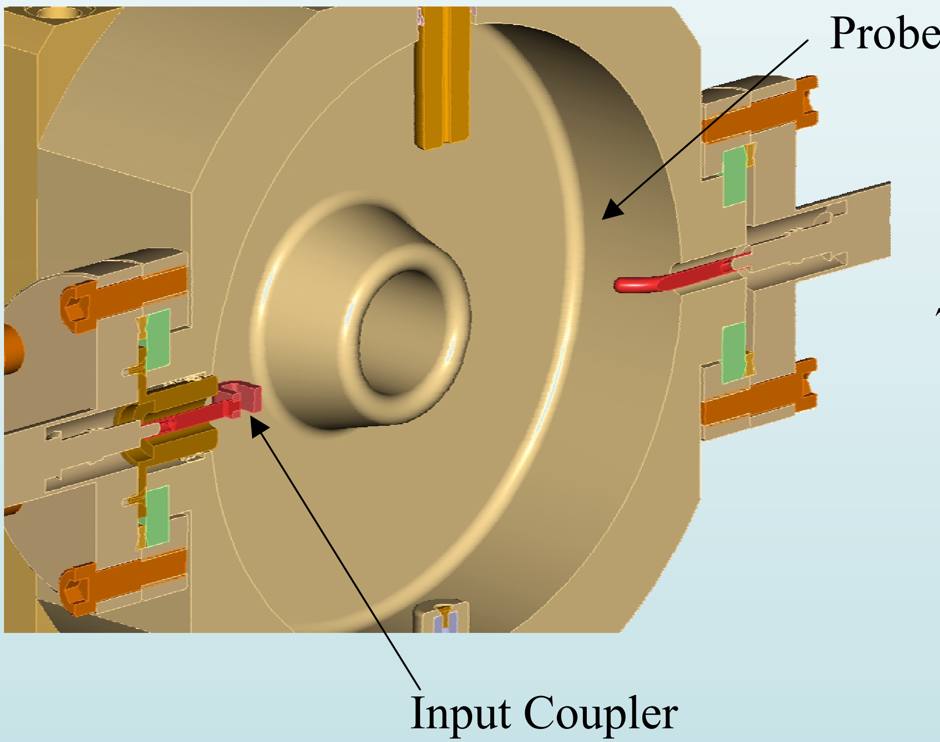
EMMA Cell Layout Plan

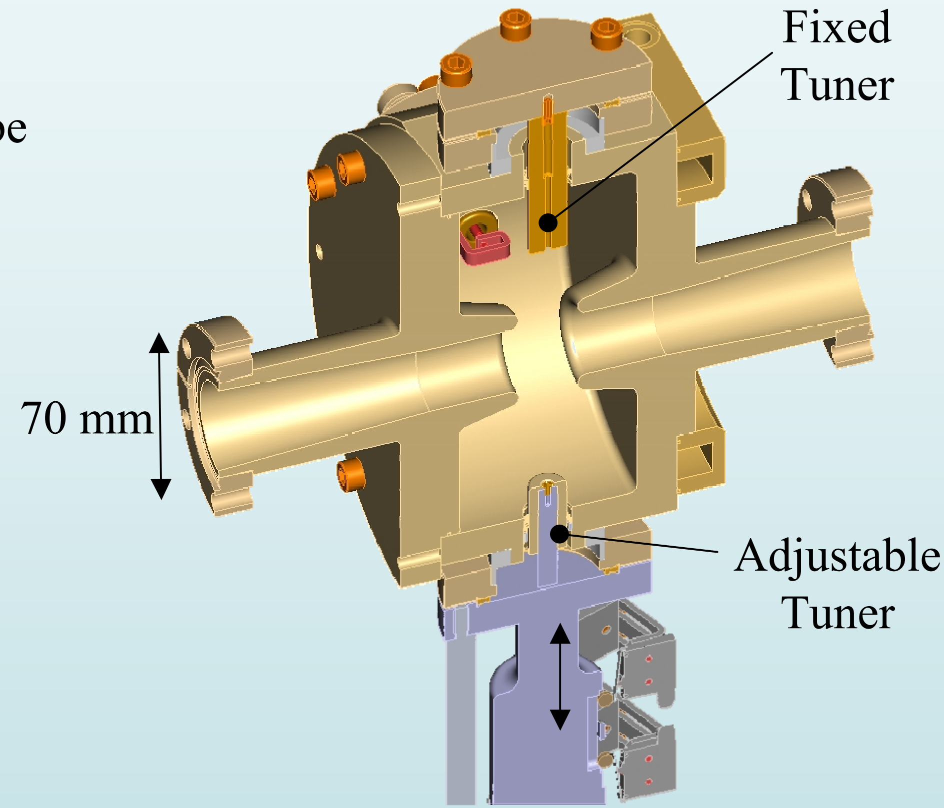


EMMA Cell in 3D



EMMA Cavity: Modified ERLP Buncher Cavity



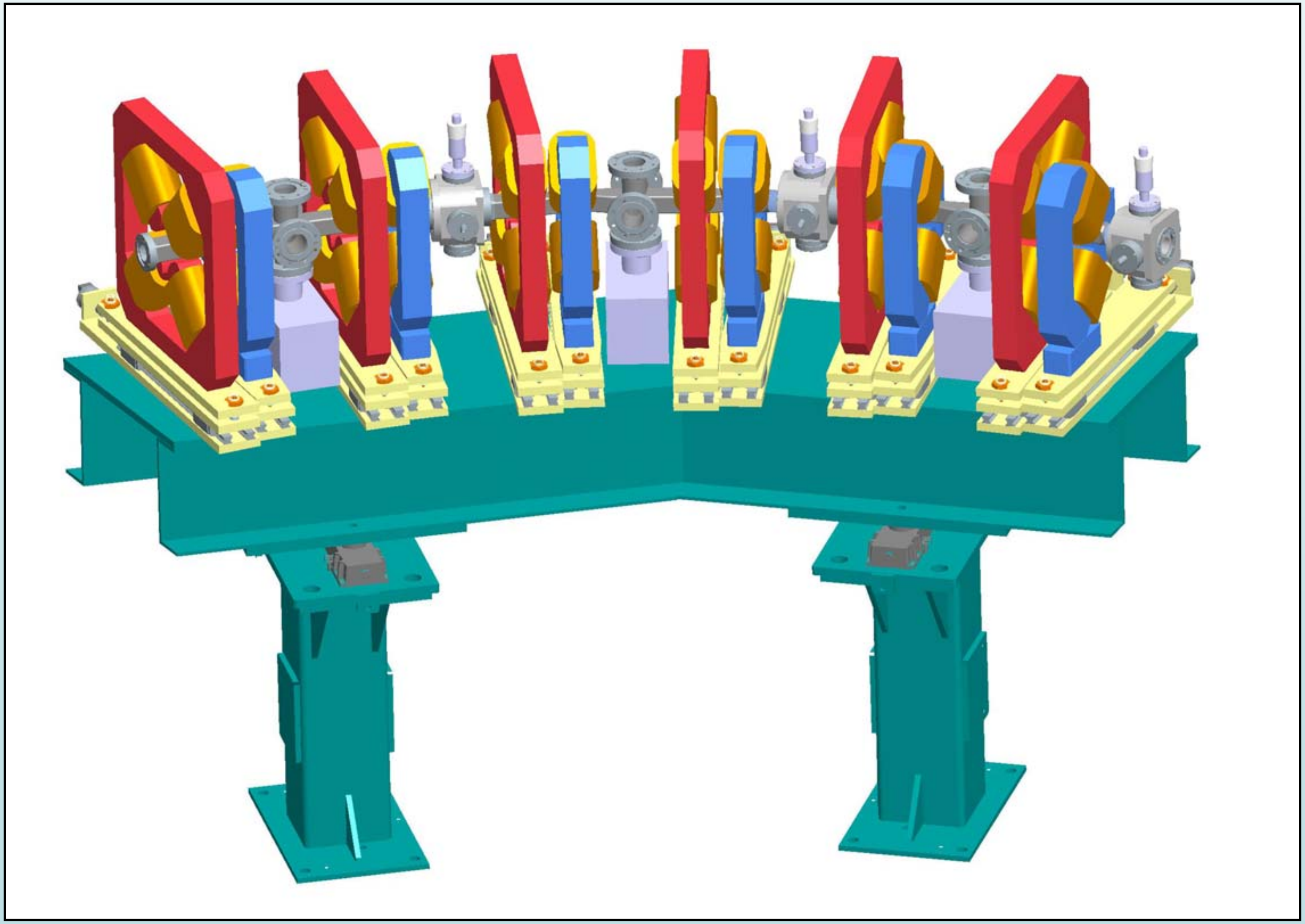


- 1.3 GHz Operating frequency
- OFHC copper construction
- Body machined from 2 pieces
- Vacuum brazed assembly
- CF flanges TIG welded

FZ Rossendorf design, modified for ERLP, manufactured by Vacuum Generators (UK)

EMMA Girders

42 lattice cells assembled on 7 girders. Each 6-cell girder will be 2.33 m long.



Timescales for EMMA

• Design review on January 4th at DL to freeze major elements of the specification

• Official project start date is April 2007

Implementation phase of Project:

• 12 months detailed design phase
• 16 month procurement phase in parallel
• 8 month off line assembly and test
• 6 months installation and testing in the ERLP Accelerator Hall
• 6 month of full ring studies
• Some overlapping of the above to make a 3½ year programme

Concept design complete	Dec 30th 2005
Feasibility design complete	Mar 30th 2007
Detailed design	Mar 10th 2008
Procurement complete	Aug 1st 2008
Construction phase complete	Jul 23rd 2009
Commissioning with electrons complete	Sep 17th 2009
Phase 1 full ring studies complete	Mar 5th 2010
Phase 1 advanced ring studies complete	Jul 9th 2010

The ERLP & 4GLS Team

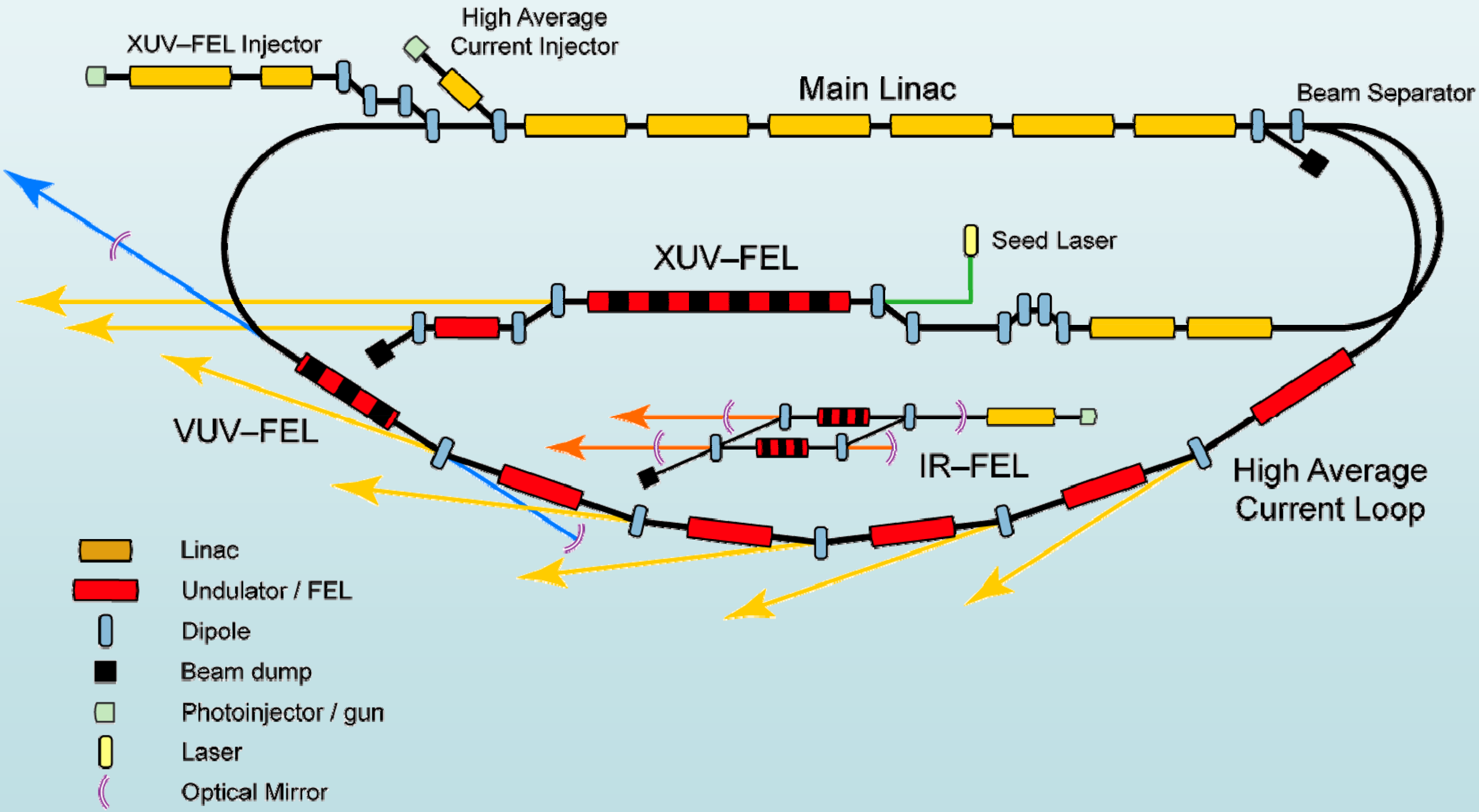
At Daresbury Laboratory

Thank you for listening ……
…… And thank you to JLab

ERLP Status January 2007

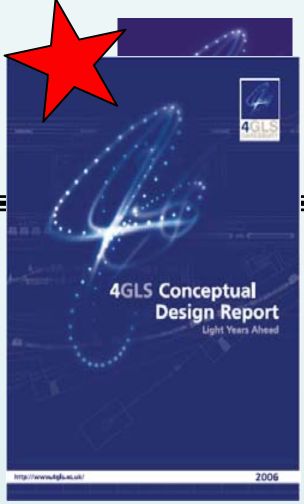
Lee Jones
ASTeC

4GLS



XUV–FEL Injector
High Average Current Injector
Main Linac
Beam Separator
XUV–FEL
Seed Laser
VUV–FEL
IR–FEL
High Average Current Loop
Linac
Undulator / FEL
Dipole
Beam dump
Photoinjector / gun
Laser
Optical Mirror

4GLS Design Studies update



- 4GLS Conceptual Design report (CDR)
  - April '06
- 4GLS Design Configuration Report (DCR)
  - Dec '06
- 4GLS Technical Design Report
  - Autumn '07

- Baseline costing exercise of 4GLS design v1.0 (CDR) completed
- First round of layout refinement 4GLS v1.1
- Started work on S2E
- Work on detailed accelerator physics issues
- R&D on SCRF for 4GLS
- FEL simulations and seeding
- …

EuroFEL SRF Injector Investigations

- Investigation on injectors for high current ERLs (4GLS)
  - A comprehensive report has been issued and accepted by the EuroFEL science committee, outlining the full requirements of high current operation and a suggested R&D plan
- SRF Gun Development (collaboration with BESSY & FZR)
  - Simulations of existing design have been carried out
  - Work has commenced on suitable upgrades for higher current operation

EURO FEL	Current Design		Design Goal
Energy	10 MeV	→	1GeV
Current	1 mA	→	100 mA
Eacc	10 MV	→	5-10 MV
Qbunch	77 nC	→	77 nC
RF Power	10 kW	→	0.5-1 MW