RSC meeting Oct.28, 2015

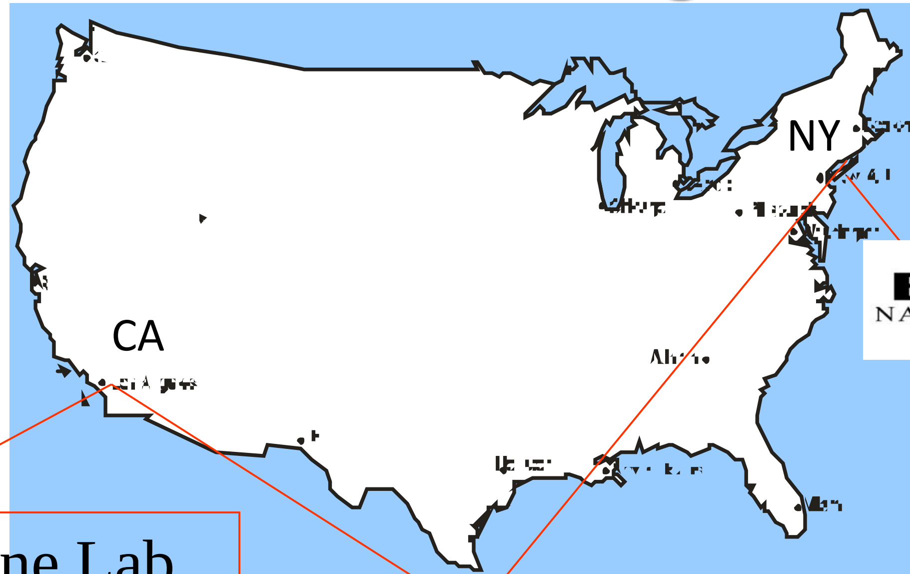
100-TW CO_2 laser as a source of ionizing radiation

Igor Pogorelsky

ACCELERATOR TEST FACILITY

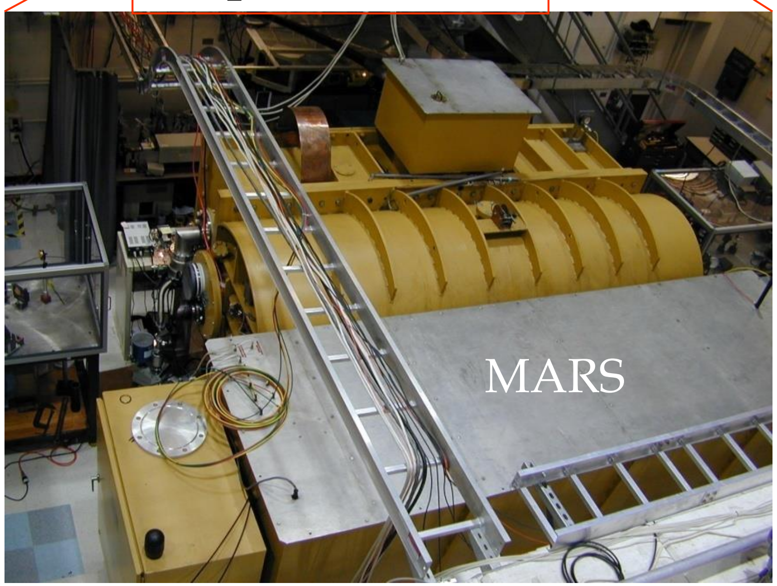
BROOKHAVEN NATIONAL LABORATORY

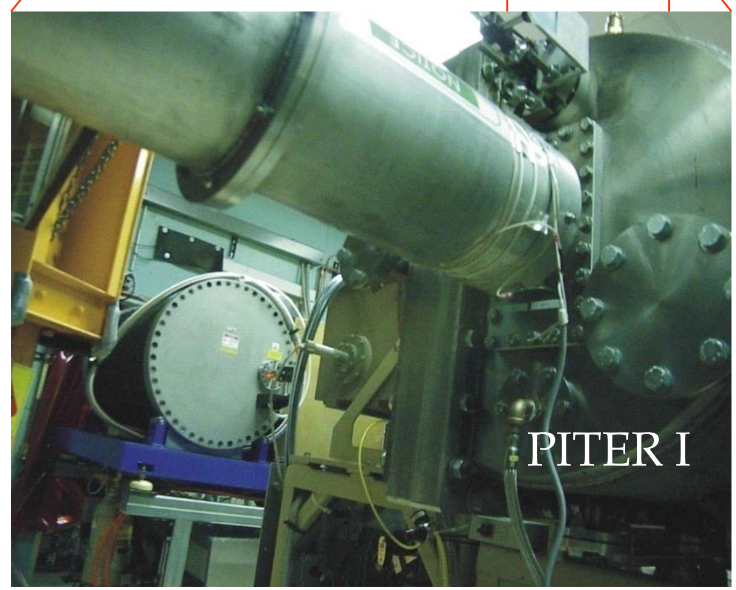
CO_2 Laser Facilities for Strong-Field Physics



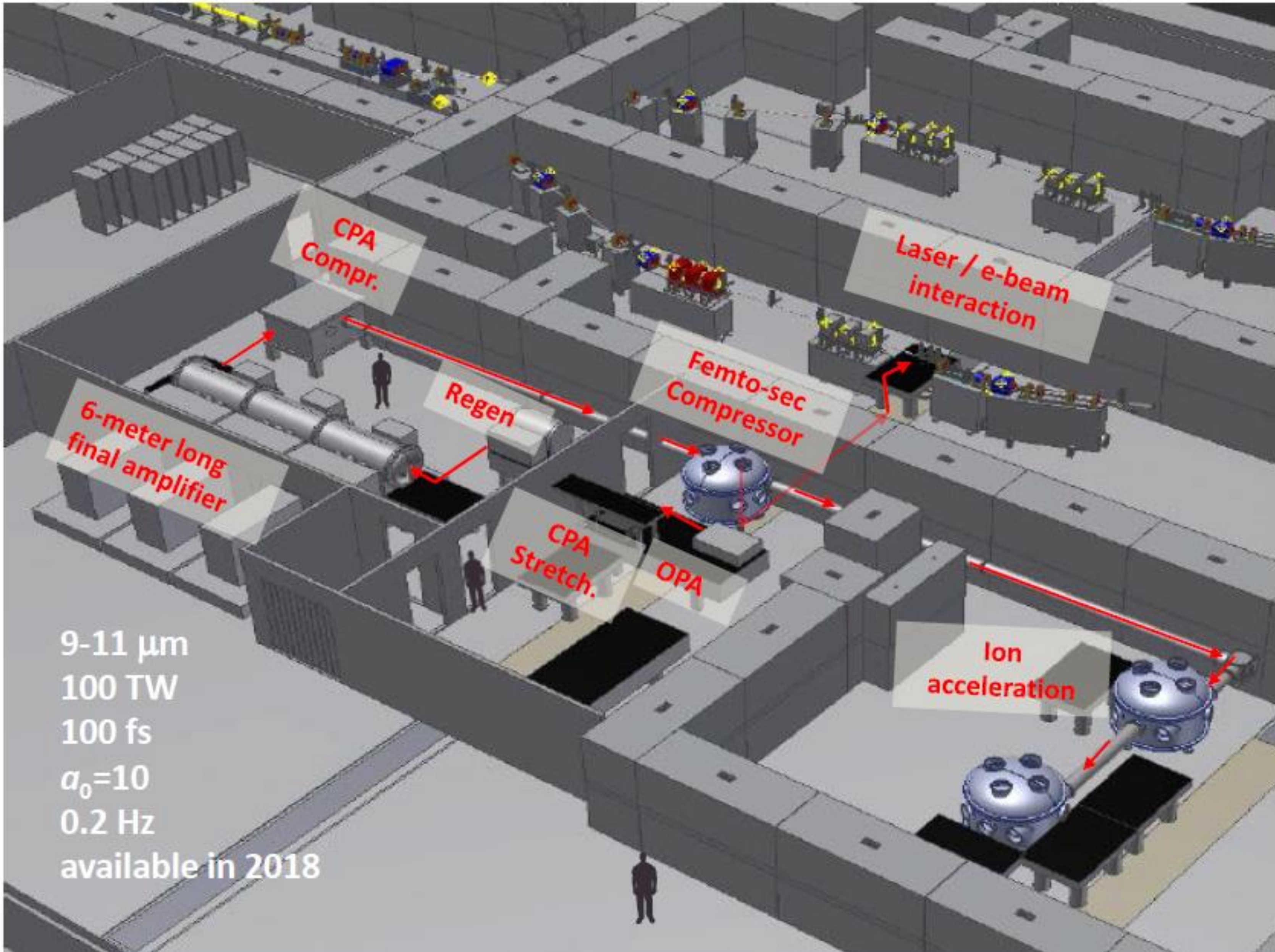
Neptune Lab.

ATF

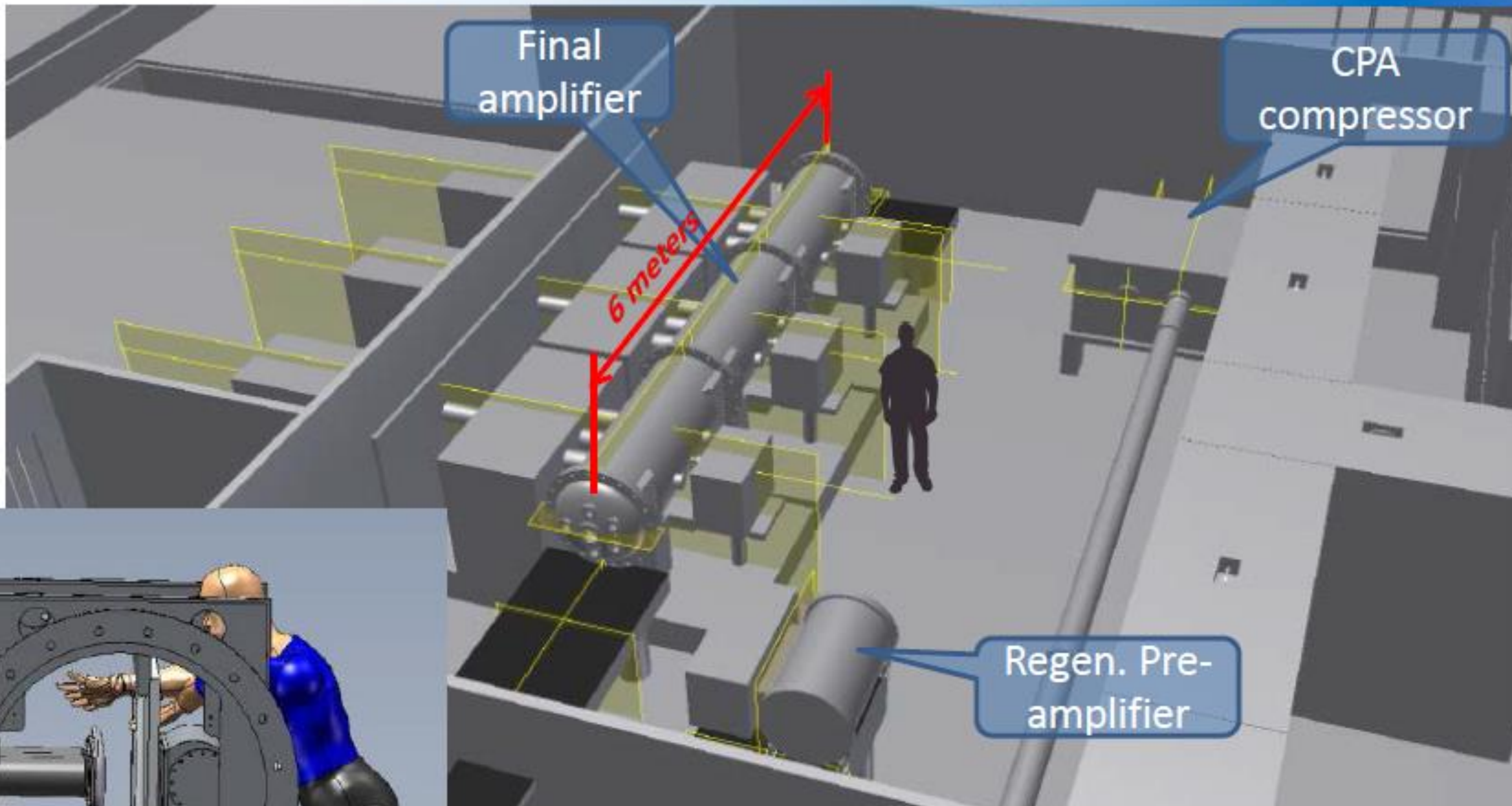


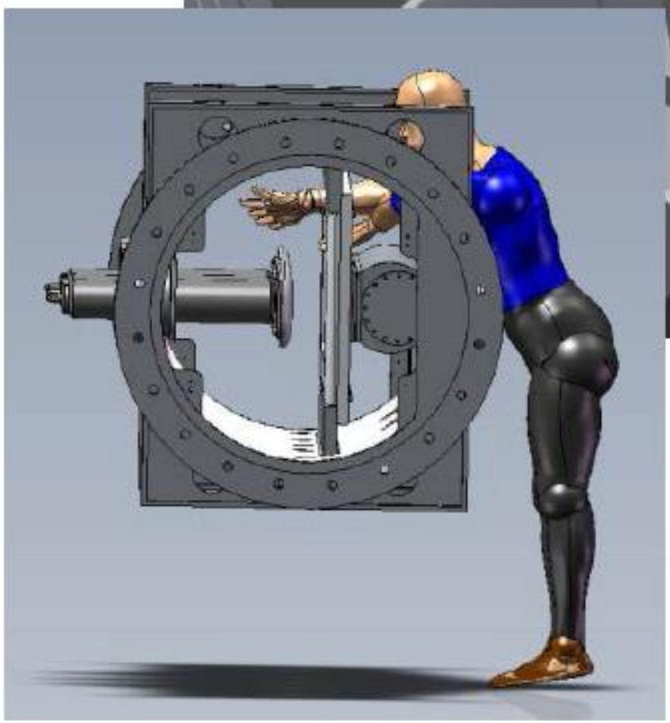


Developing 100 TW CO_2 laser

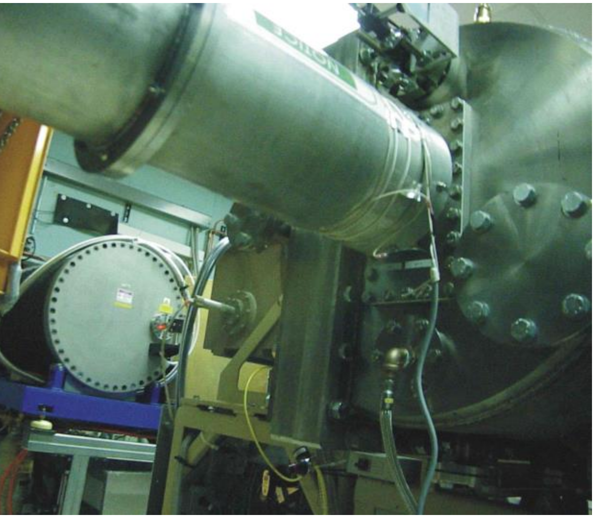

CPA
Compr.
Laser / e-beam
interaction
Femto-sec
Compressor
Regen
6-meter long
final amplifier
CPA
Stretch.
OPA
Ion
acceleration
9-11 µm
100 TW
100 fs
a_0=10
0.2 Hz
available in 2018

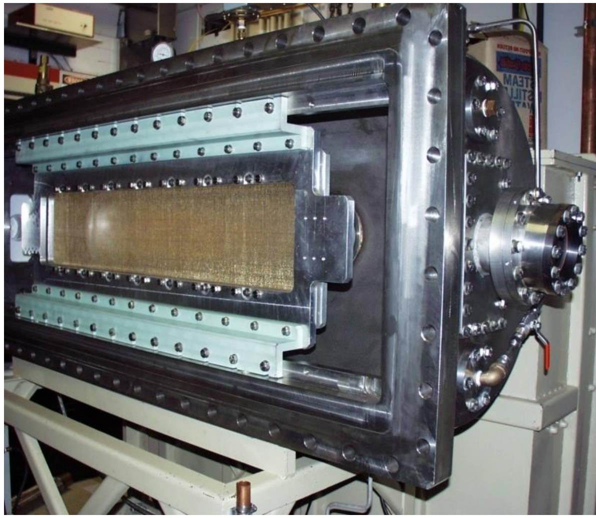
6-meter long CO_2 laser final amplifier

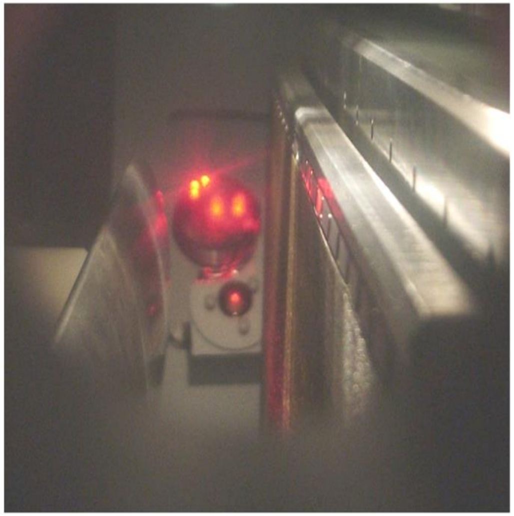


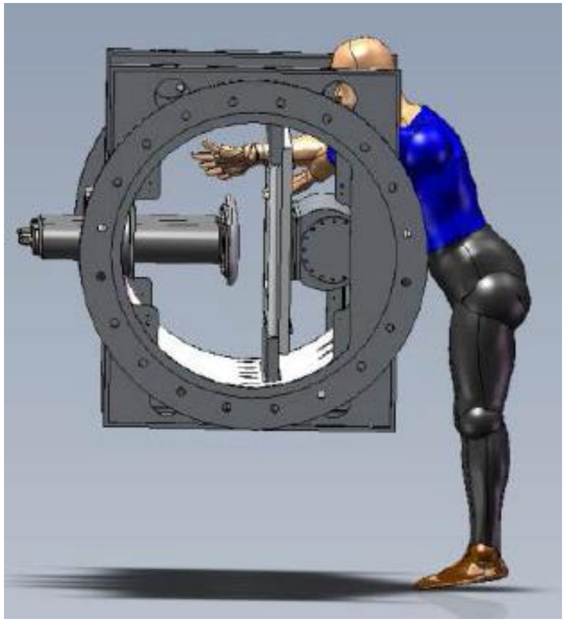


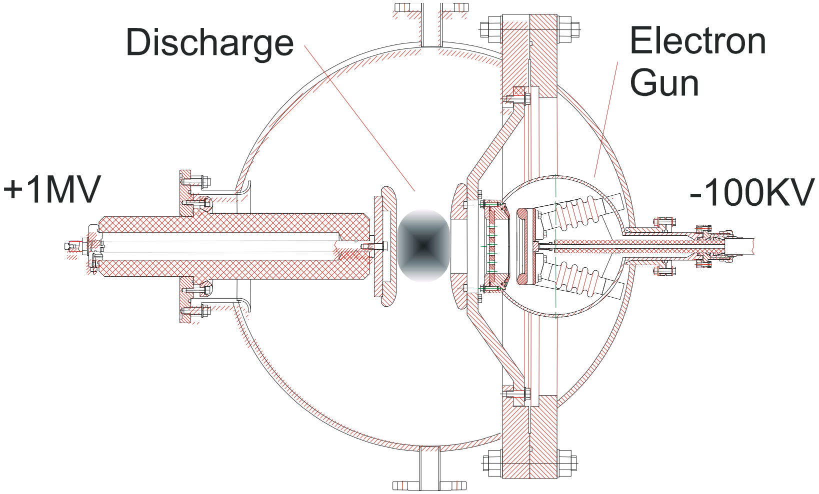
Main amplifier











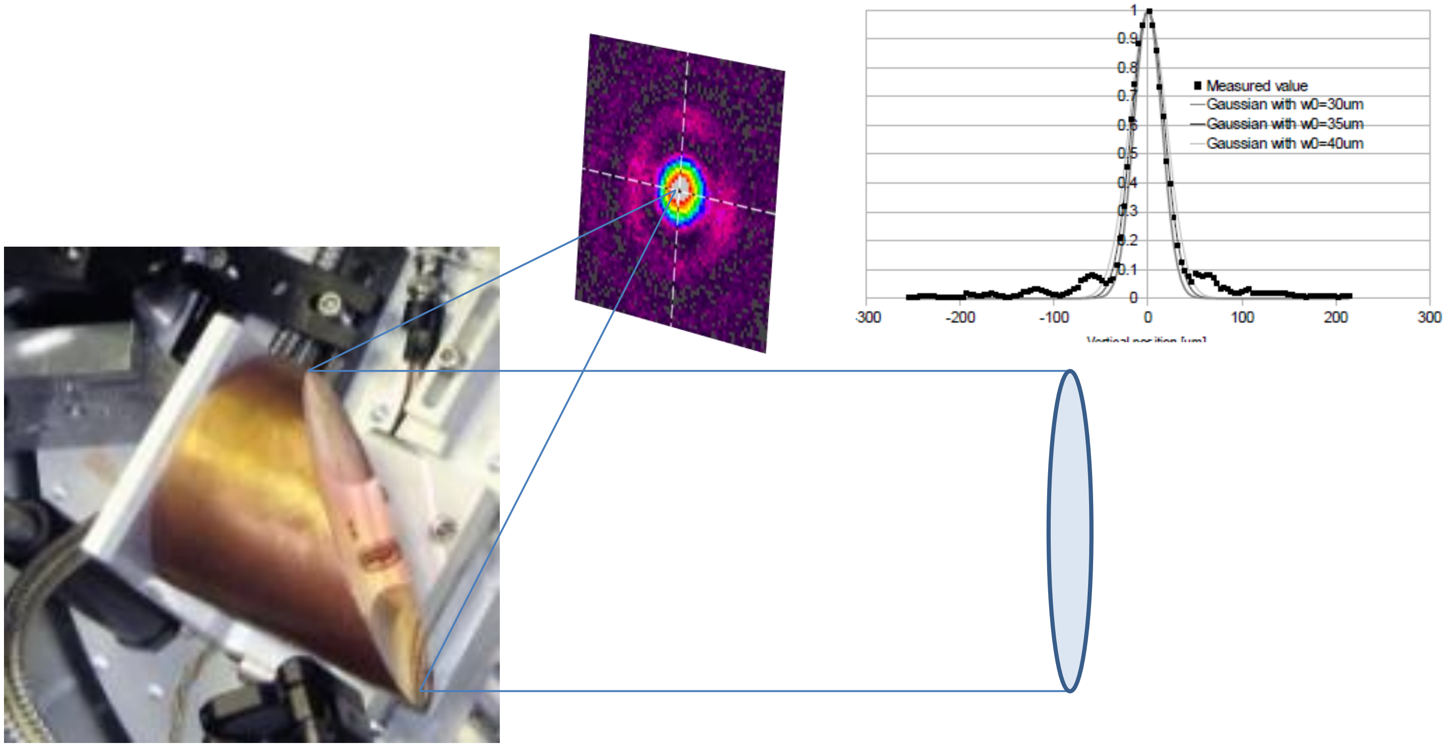
Amplifier cross-section diagram

Table 1: Main parameters of the ATF-II CO_2 laser

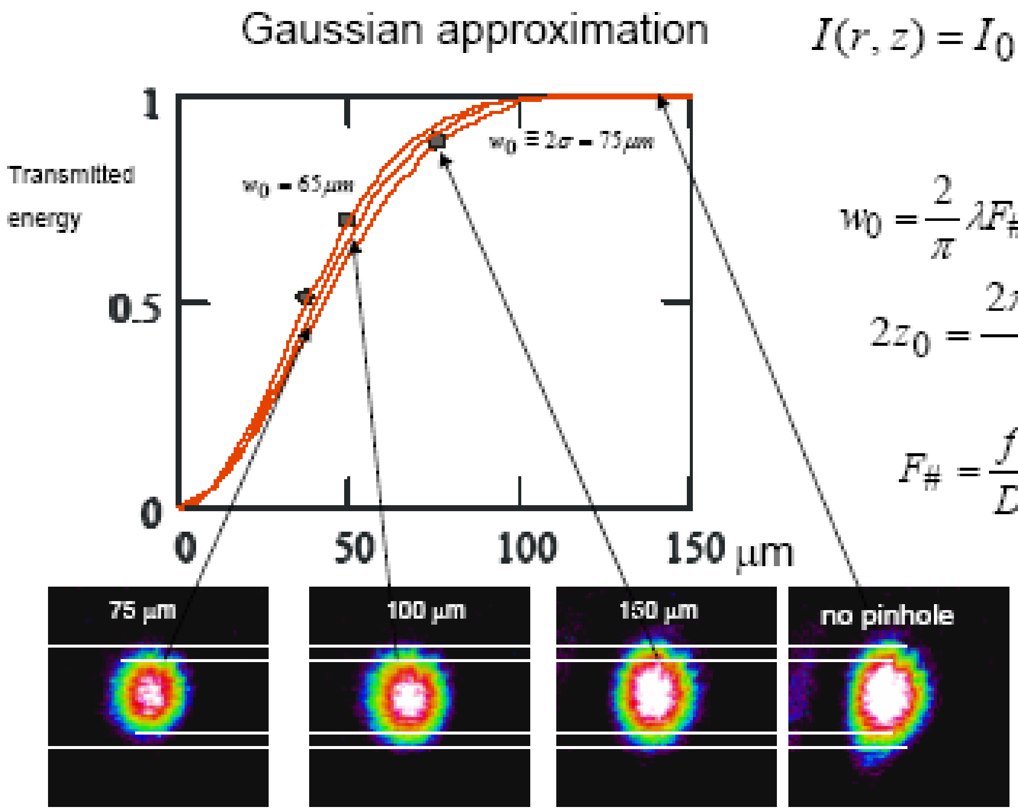
Parameter	Value
Laser wavelength	9-10 μm
Peak power	100 TW (25TW)
Pulse energy	10 J (50J)
Pulse duration	100 fs (2 ps)
Repetition rate	0.2 Hz
Gas content	CO_2:N_2:He
Gas pressure	10 atm
Main discharge	750 kV, 6 kJ
Internal x-ray preionizer	100 kV, 100J 3 Roentgen

- High-pressure main discharge is the source of thermal electrons that excite laser molecules.
- In high-vacuum preionizer, electrons are accelerated to 100 keV to be converted to bremsstrahlung x-rays penetrating the main discharge volume.
- X-rays are stopped in a massive Al electrode and 22.5-mm thick stainless steel shell.
- No background radiation is detected by a chipmunk.

Laser focus


Measured value
Gaussian with w0=30um
Gaussian with w0=35um
Gaussian with w0=40um
-300
-200
-100
0
100
200
300

Study of the laser focus

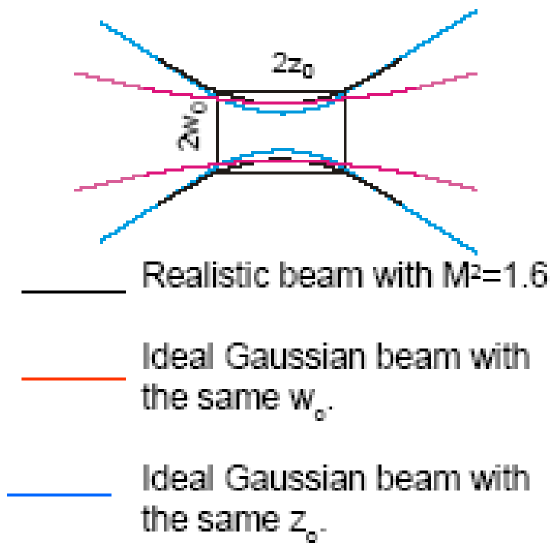


$$I(r,z) = I_0\left[\frac{w_0}{w(z)}\right]^2 \exp\left[-\frac{2r^2}{w^2(z)}\right]$$

$$w_0 = \frac{2}{\pi}\lambda F_{\#} M^2$$

$$2z_0 = \frac{2\pi w_0^2}{\lambda}$$

$$F_{\#} = \frac{f}{D}$$



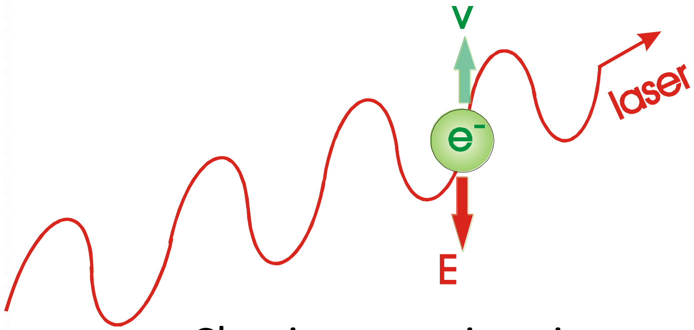
Laser focus transmitted through pinholes of 75-150 μm dia imaged on IR camera.

Gaussian approximation with w_0=65 μm is the best fit to the observed transmission through pinholes.
For ideal diffraction-limited beam, such focus corresponds to $F_{\#}$=10 and double Rayleigh distance 2.5 mm.
Instead, we measure $2z_0$=0.8 mm and $F_{\#}$=4. This means that the beam has M^2=1.6.

<u>Conclusions</u>:
- Laser intensity 10^{16} W/cm^2.
- Target position shall be controlled with 100-200 μm accuracy.

Day 1

Ionizing radiation from IR laser focus



Initial electrons produced via multi-photon or tunnel ionization, then multiplied via avalanche ionization.

Energy of the electron quiver motion in the laser field:

Classic approximation

$$\dot{v} \sim \frac{eE}{m} \Rightarrow v \sim \frac{\dot{v}}{\omega} \Rightarrow F = \frac{mv^2}{2} = \frac{e^2E^2}{2mW^2}$$

note the ω^{-2} dependence

Relativistic motion

$$\epsilon = (\gamma_t - 1)m_0c^2$$

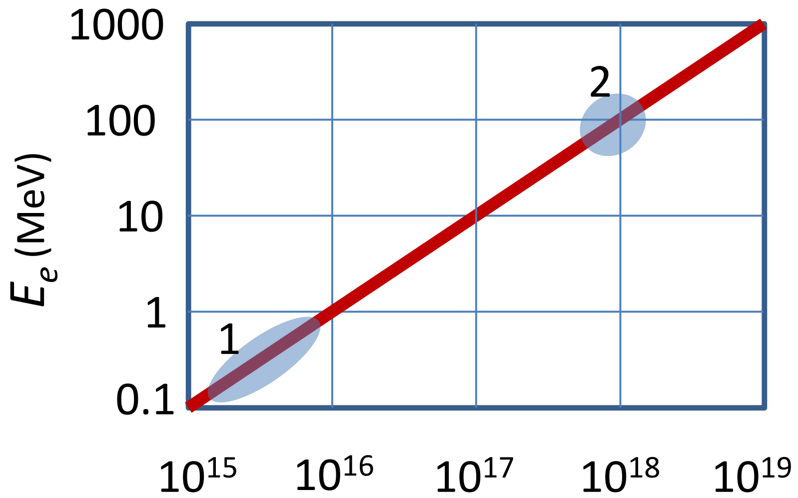
$$\gamma_t = (1 + I_L\lambda_\mu^2/1.37 \times 10^{18})^{1/2}$$

$$\epsilon \approx m_0c^2$$

for

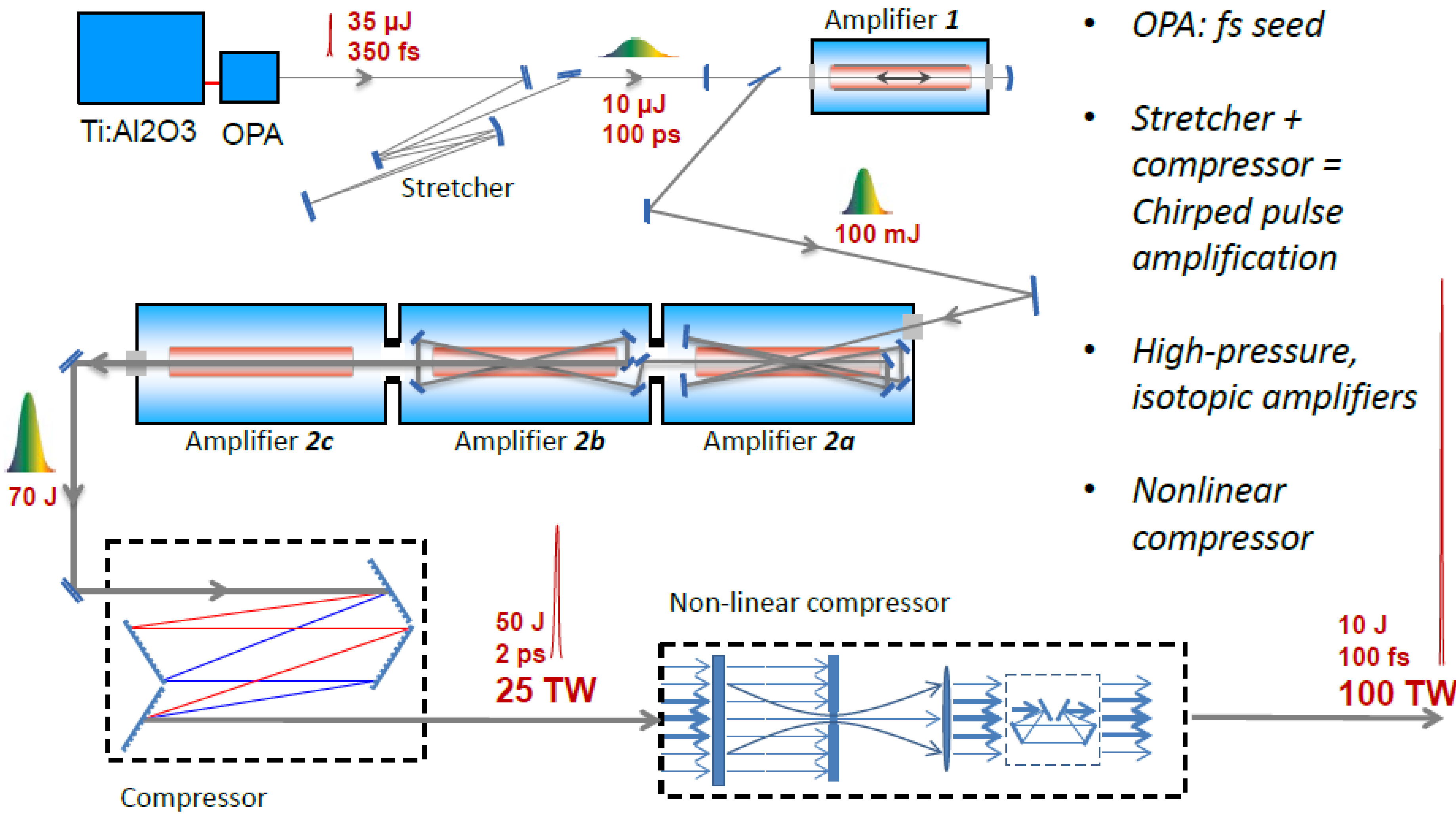
$$I\lambda^2 \sim 10^{18}\,\mathrm{Wcm}^{-2}\mu\mathrm{m}^2$$

same λ^2 dependence



1st case – in CO_2 laser room
2nd case – in Experimental Hall

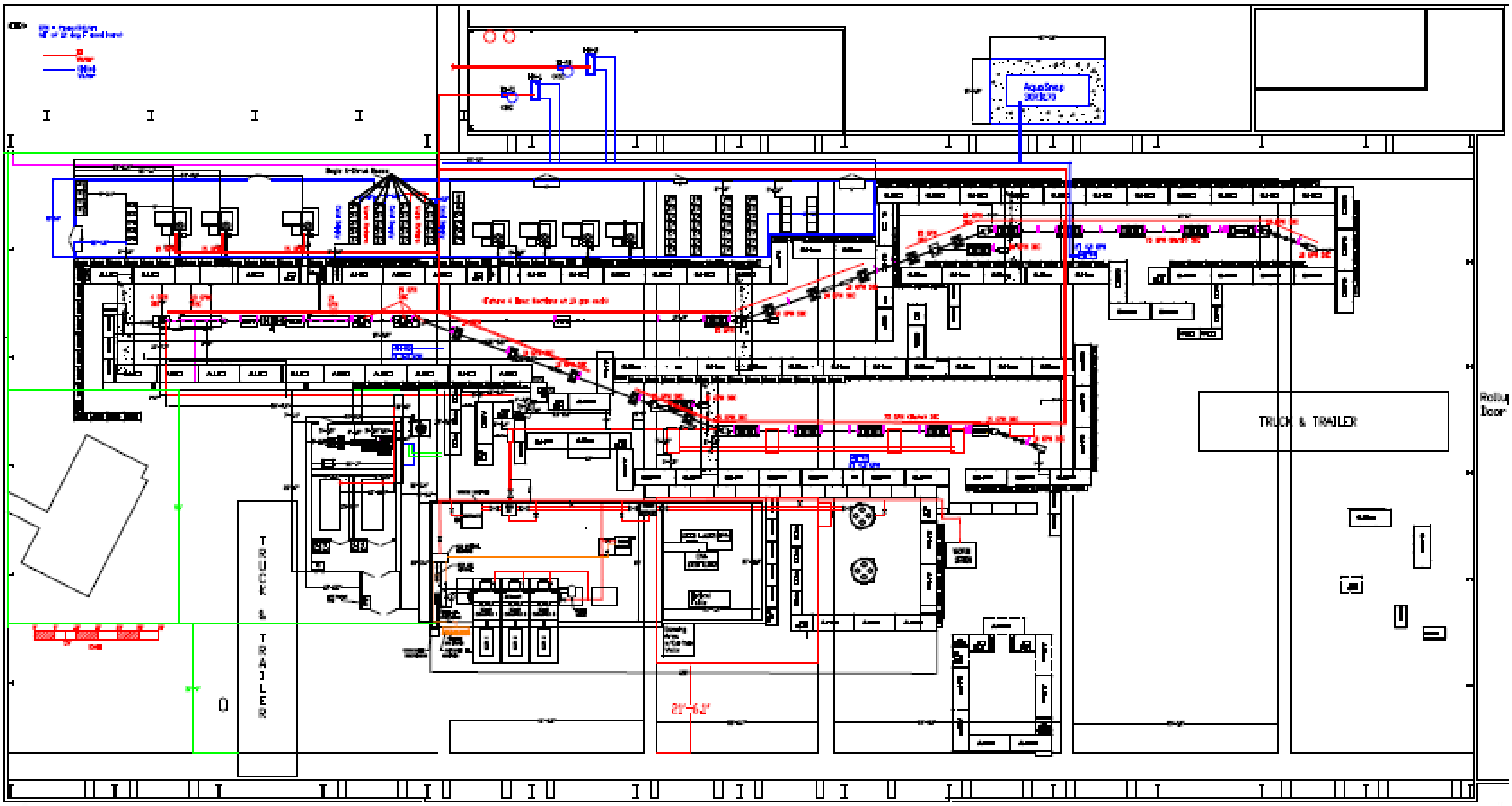
100TW CO_2 concept laser



Collection of innovations:

- *OPA: fs seed*
- *Stretcher + compressor = Chirped pulse amplification*
- *High-pressure, isotopic amplifiers*
- *Nonlinear compressor*

ATF-II layout



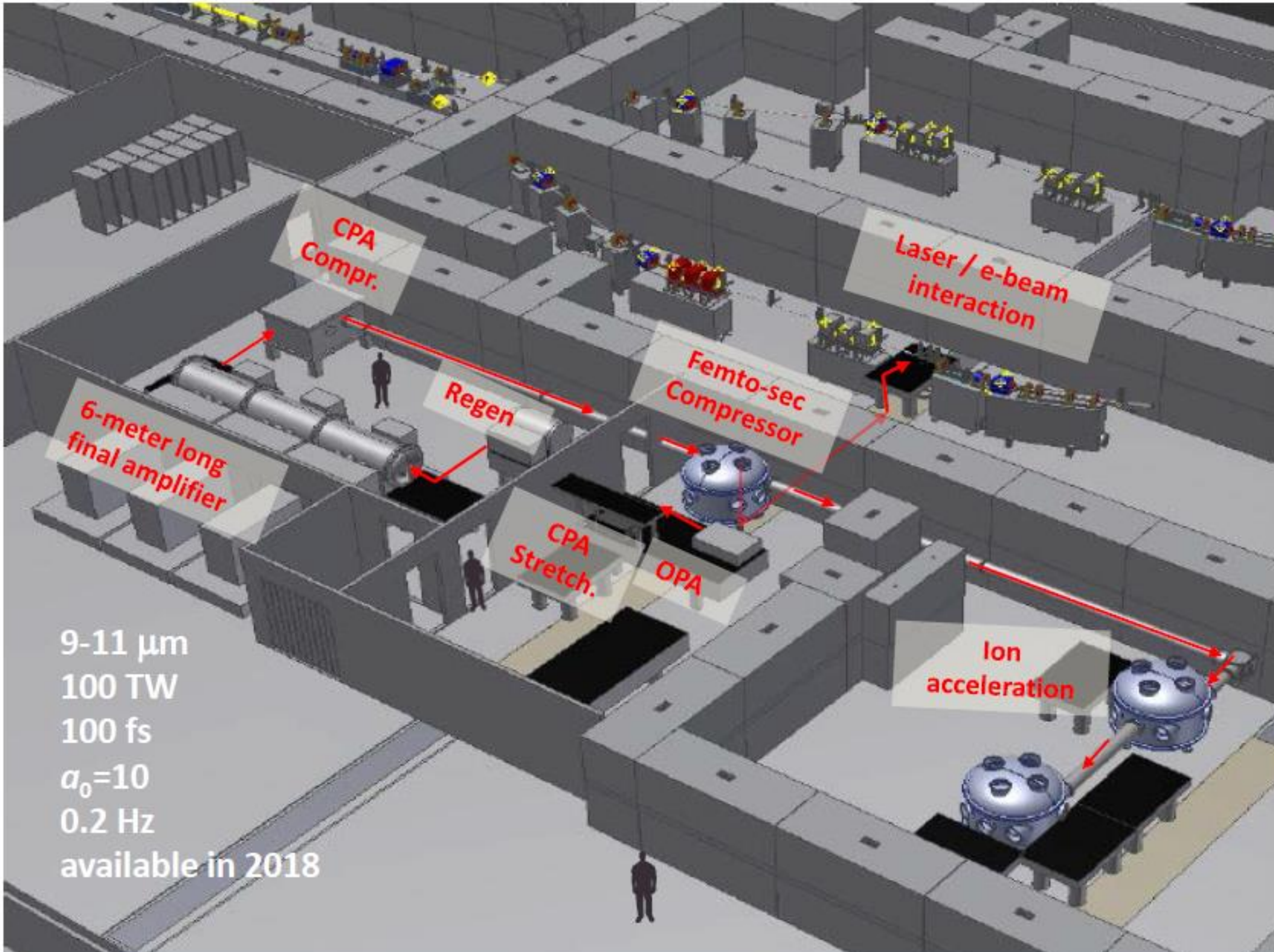

CPA
Compr.
Laser / e-beam
interaction
Regen
Femto-sec
Compressor
6-meter long
final amplifier
CPA
Stretch.
OPA
Ion
acceleration
9-11 μm
100 TW
100 fs
a0=10
0.2 Hz
available in 2018

Table 2: Operating Parameters for a Nonlinear Compressor

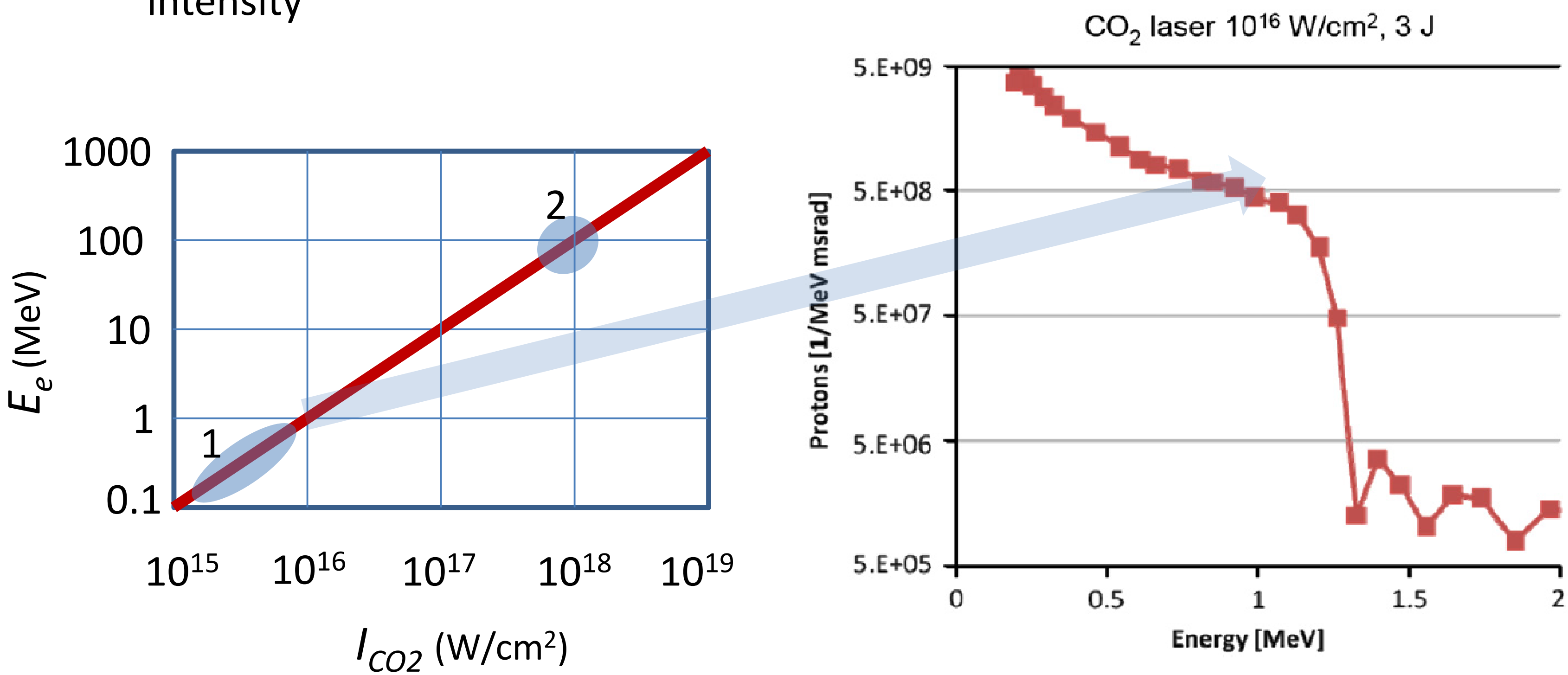
Parameter	Routine	Maximum	Comments*
Laser energy	2 J	10 J	
Laser intensity	<10^15 W/cm^2	<10^16 W/cm^2	
Laser pulse length	2 ps	2 ps	
Laser repetition rate	720/h	~20/h	
Primary hot electrons			isotropic
Laser deposition to hot electrons	10%	100%	
Electron temperature	<300 keV	<1 MeV	
Secondary gammas			isotropic
Electron energy conversion	<10%	10%	
Temperature	<300 keV	<1 MeV	
Secondary ions	10 nC	100 nC	isotropic
Electron energy conversion	<10%	10%	
Temperature	<300 keV	<1 MeV	

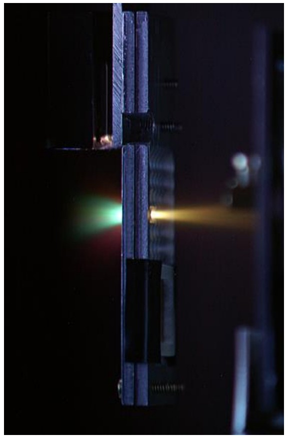
* Maximum regime in this situation corresponds to laser misalignment resulting in higher energy deposition on a target. This is a fault condition that can be spotted and corrected. That is why the accumulated number of shots per hour is substantially reduced to compare with a routine operation where most of the laser radiation propagates through a hole in the target without producing ionizing radiation.

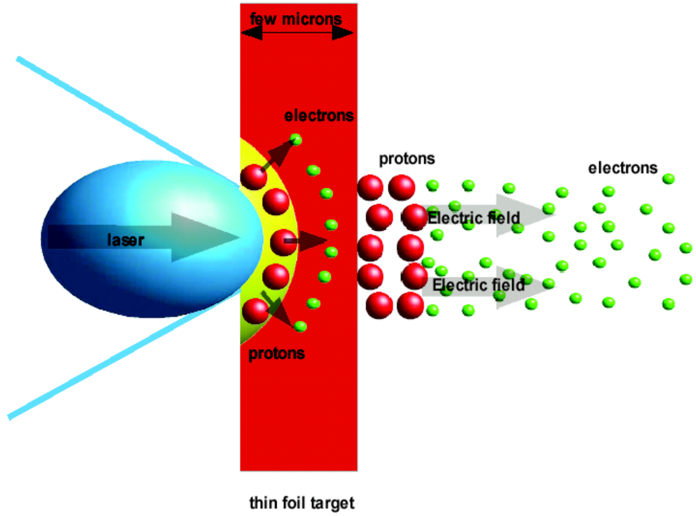
Hot electrons may accelerate ions

Dependence of electron temperature upon CO_2 laser intensity

Proton spectrum experimentally measured at CO_2 laser intensity 10^{16} W/cm^2

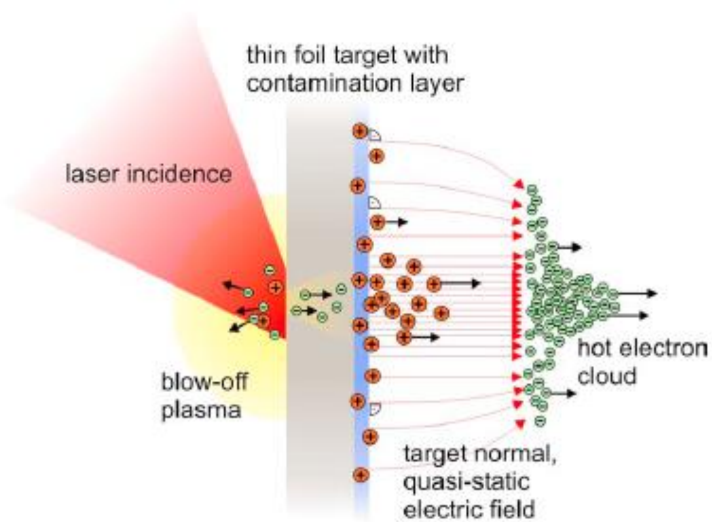






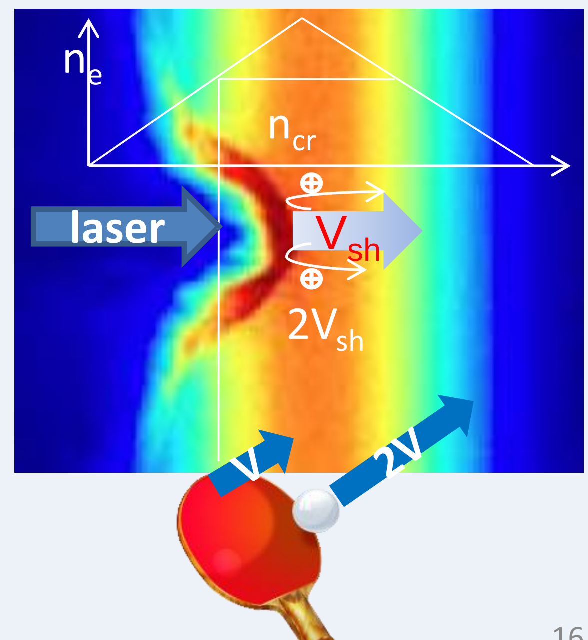
Target Normal Sheaf acceleration
(surface process)
@ $n_p >> n_{cr}$ $n_{cr} = 10^{19} cm^{-3}$

Hot electrons produced at laser focus penetrate target forming space charge separation layer and pulling light ions from surface

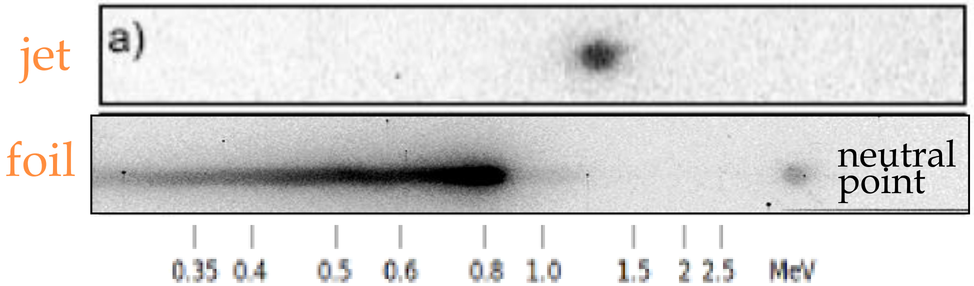


Shock wave acceleration
(volumetric process)
@ $n_p > n_{cr}$

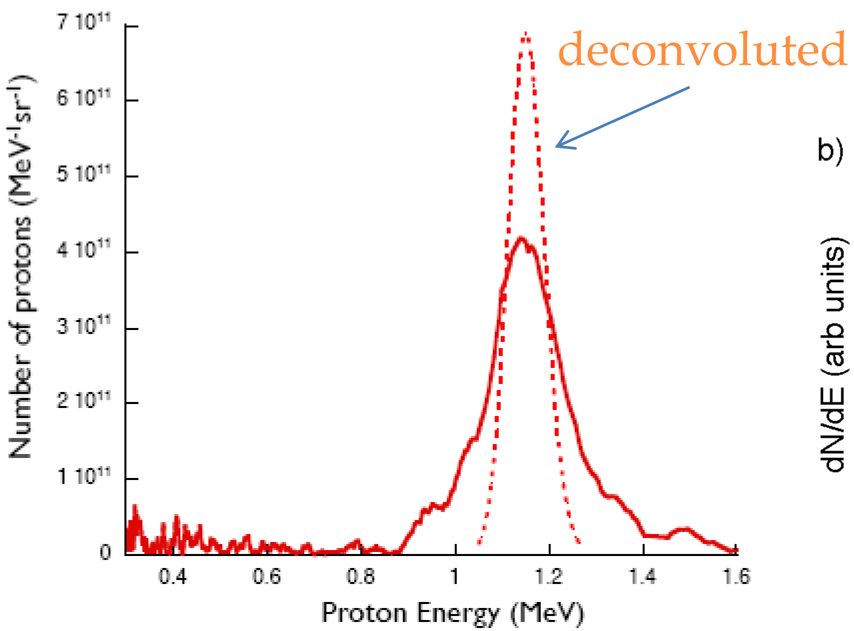
When hole boring accedes 2Mach, it launches electrostatic shock wave that reflects ions at double velocity

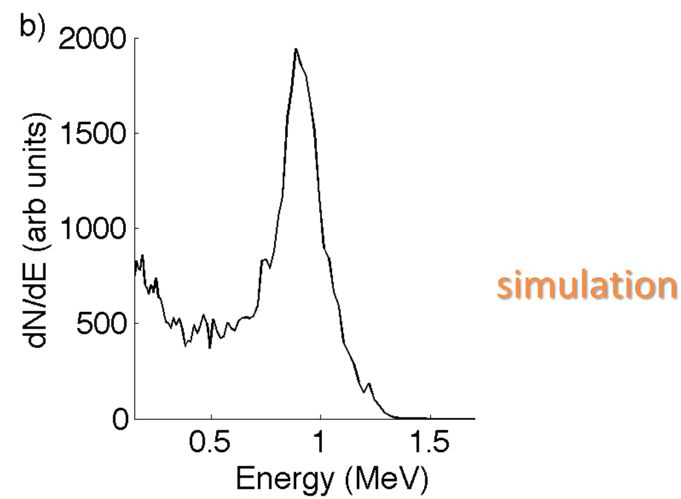


Monoenergetic protons from Hydrogen gas jet

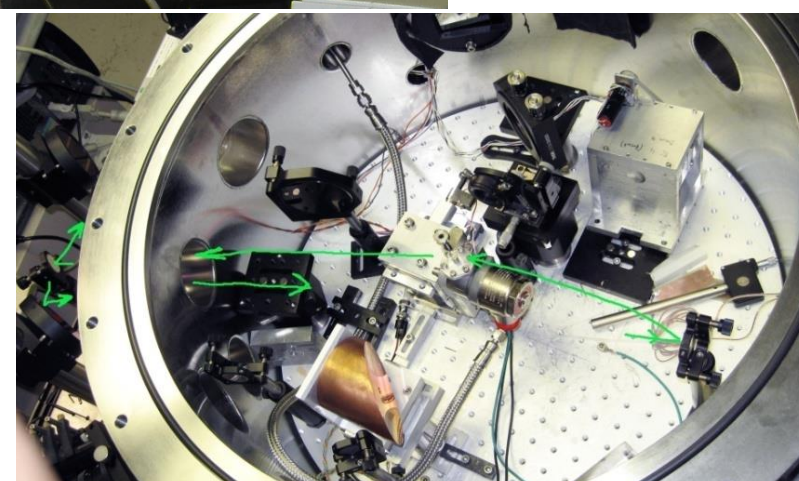


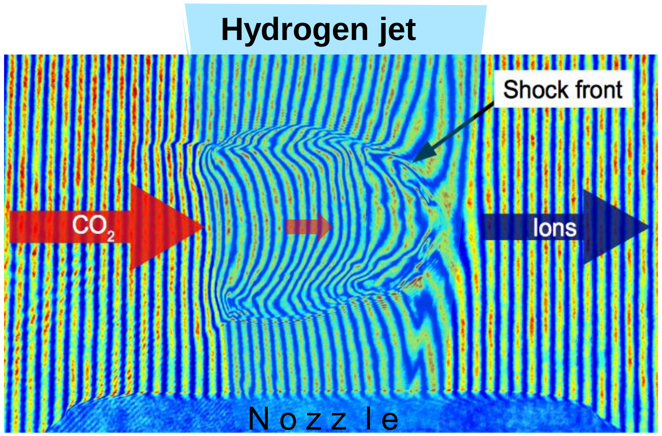
- 4% rms energy spread
- 5×10^{6} protons within 5-mrad (collected through 600 μm pinhole placed at 120 mm distance)
- spectral brightness 7×10^{11} protons/MeV/sr (300× greater than previous laser- generated ion beams)



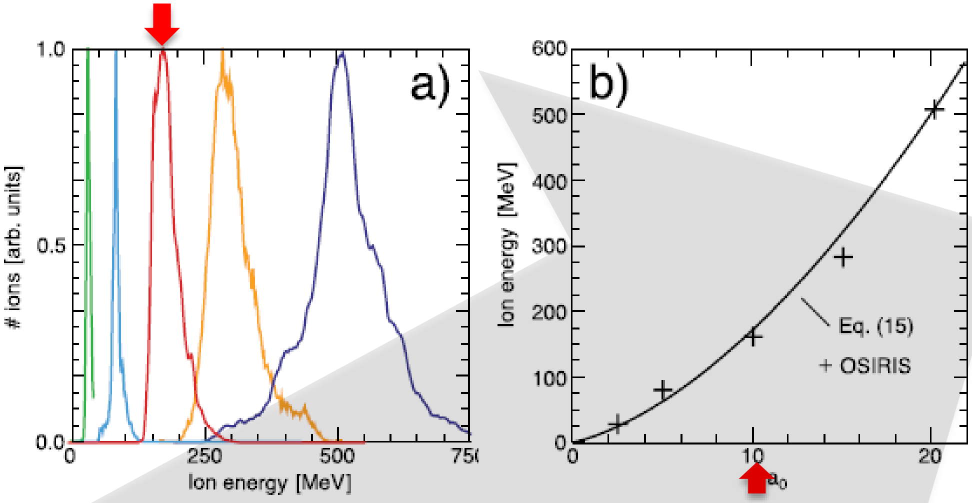


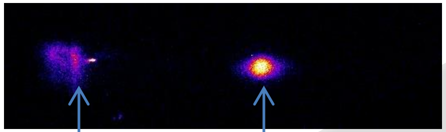
BNL experiment with gas jet





Laser-induced electrostatic shock reflects protons upon its propagation through the ionized H_2 jet.

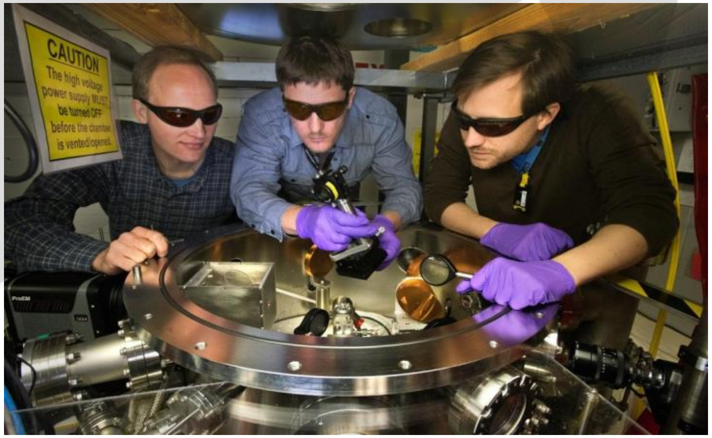




(light or neutrals)

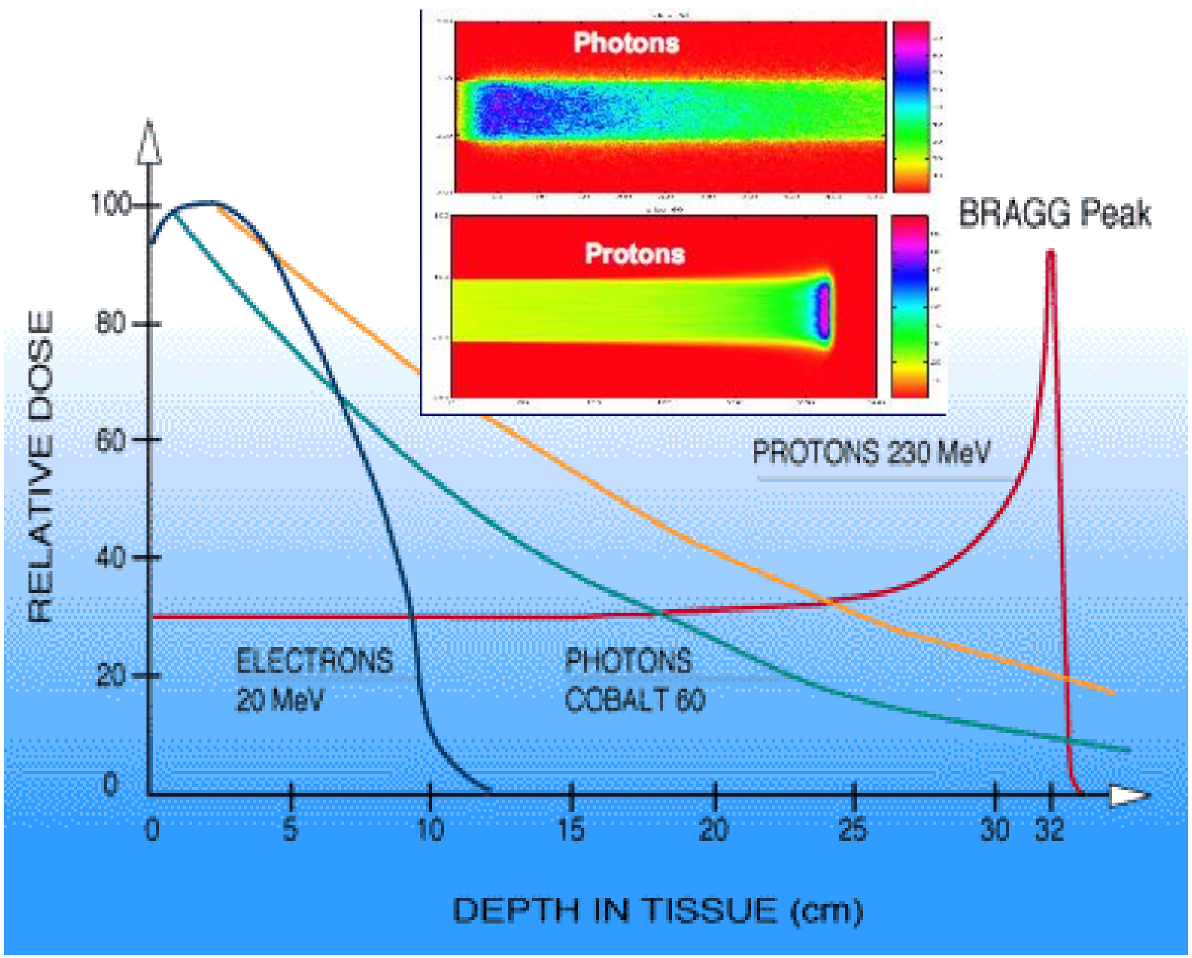
1.7 MeV protons

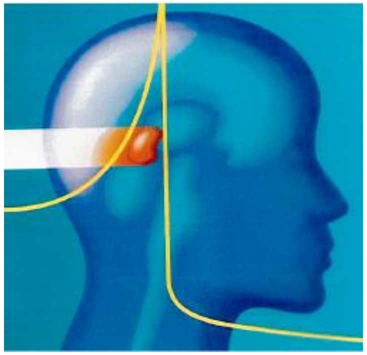
$$E_p \propto I/n_{cr}$$



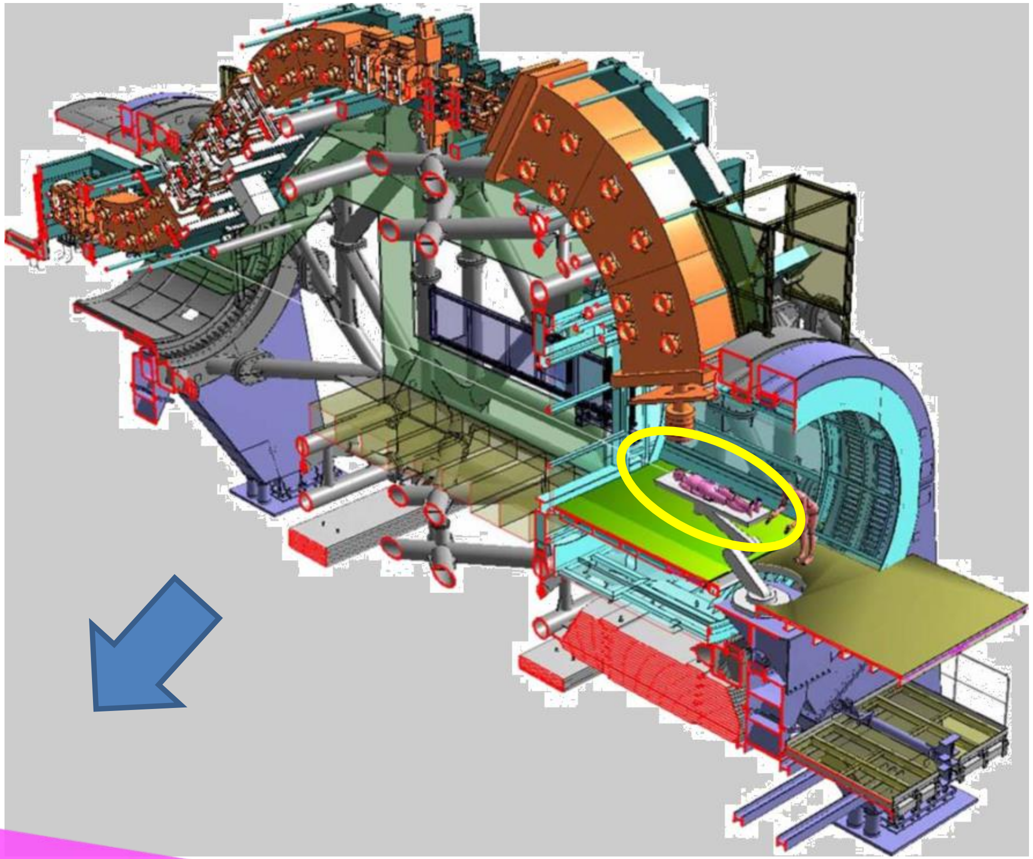
- Energy spread 10%
- Spectral brightness 10^{12} proton/MeV/str
- Proton energy up to 3.2 MeV

Aspiration for compact plasma ion accelerator – cancer therapy





Conventional gantry (670 ton)



Artist's view of laser-based therapy

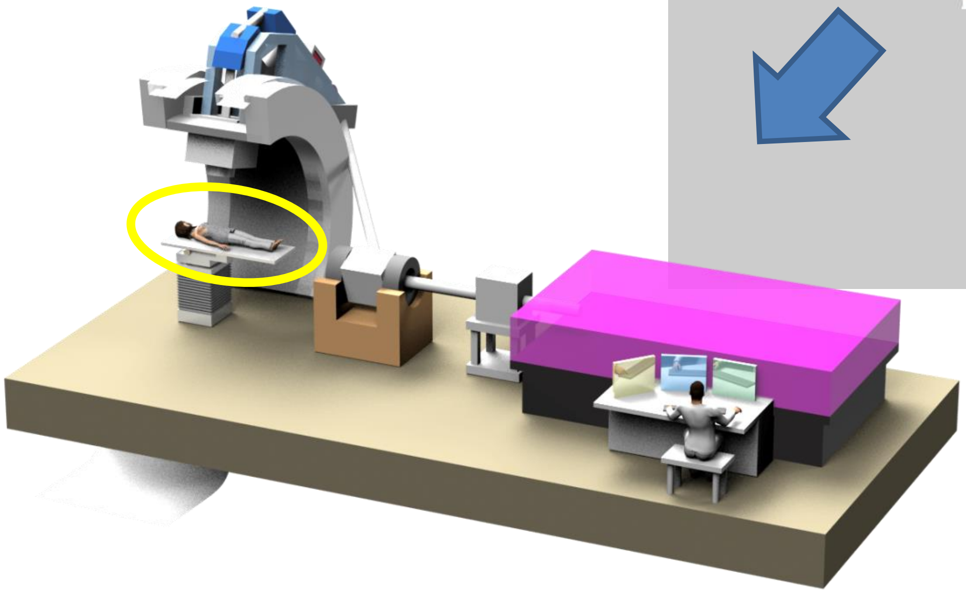
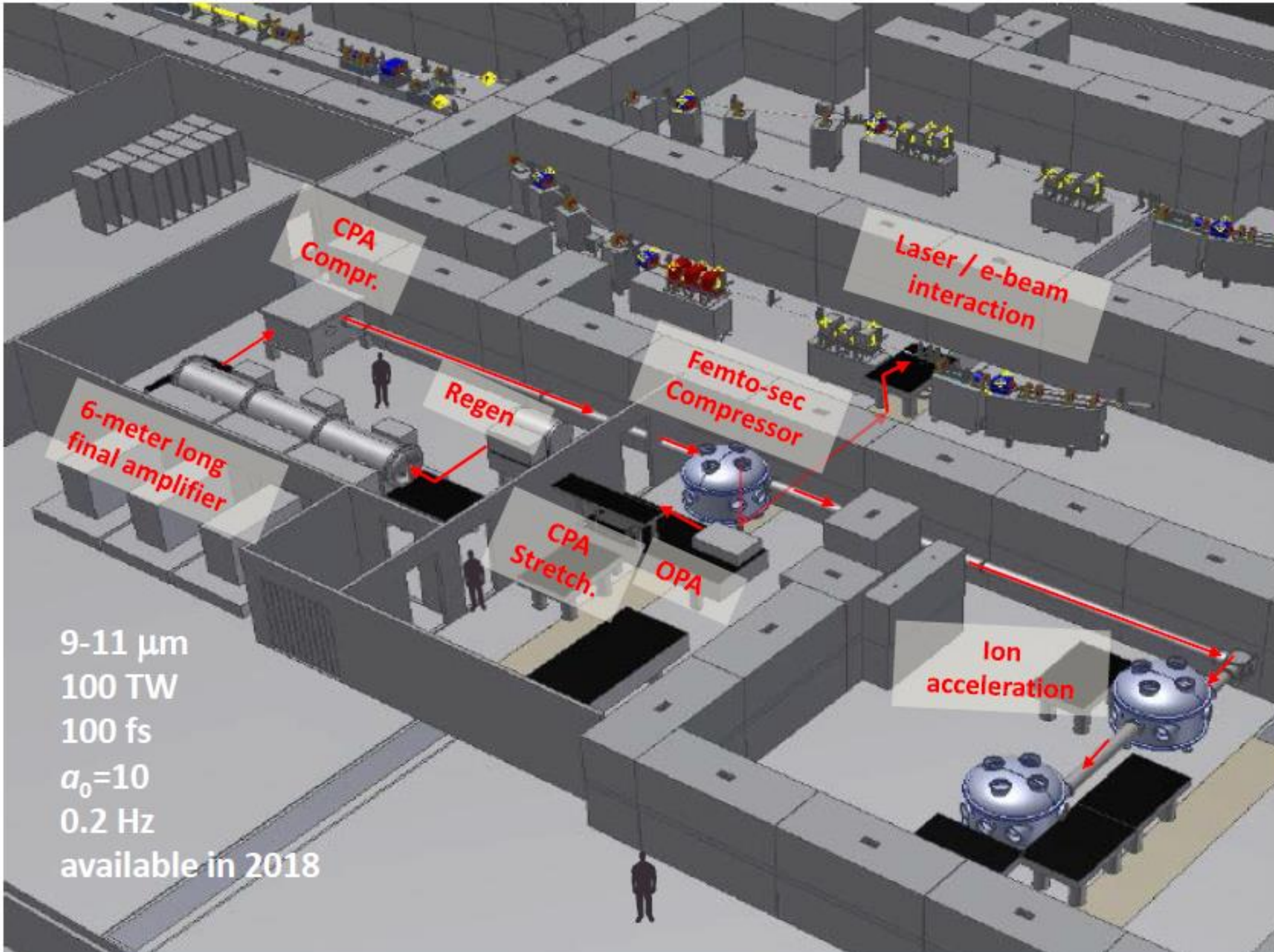


Table 3: Operating Parameters for Ion Accelerator

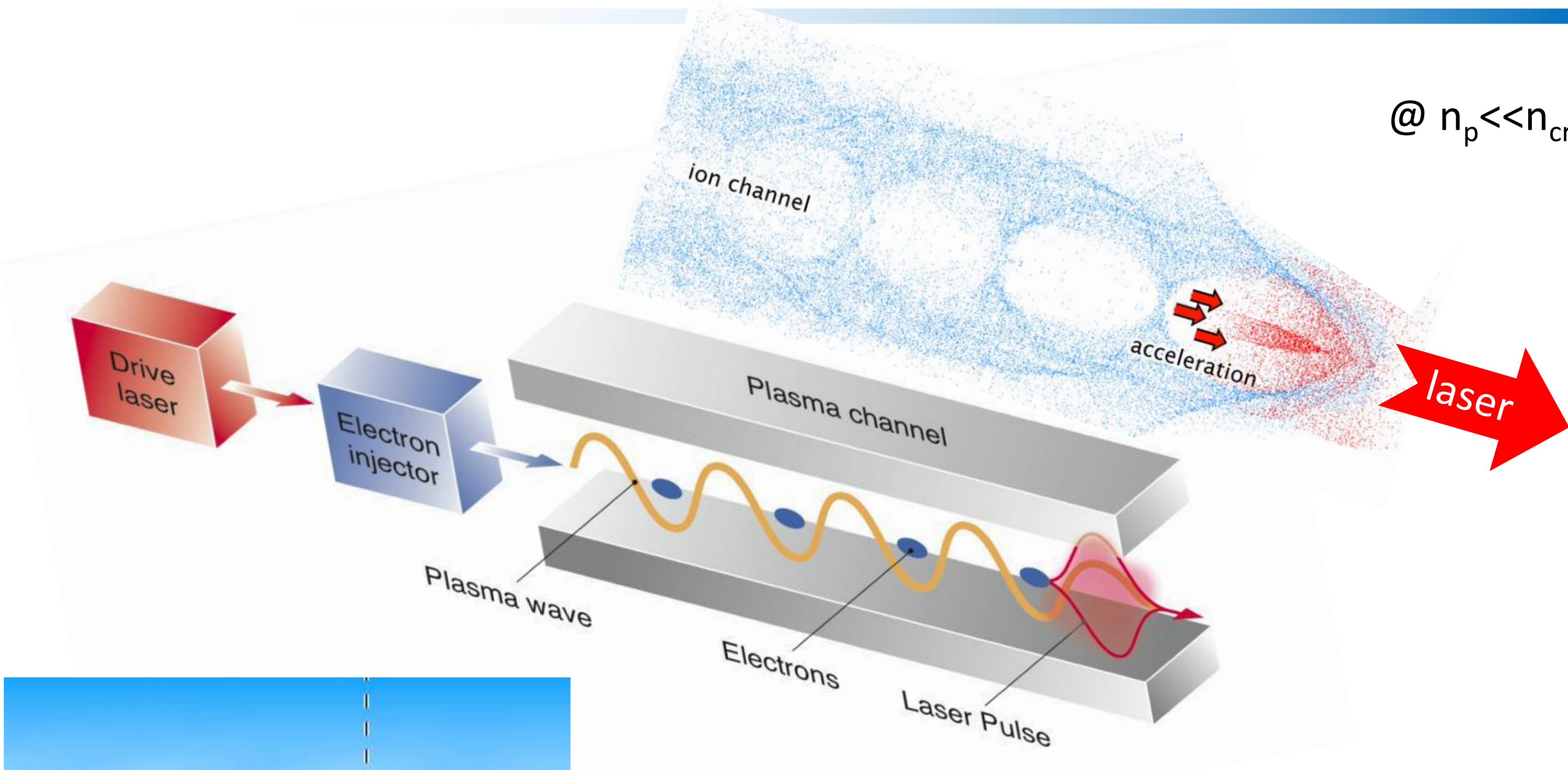
Parameter	Routine*	Maximum*	Comments
Laser energy	10 J	10 J	
Laser intensity	10^18 W/cm^2	10^18 W/cm^2	
Laser pulse length	100 fs	100 fs	
Laser repetition rate	60/h	720/h	
Primary hot electrons			isotropic
Laser energy deposition to hot electrons	100%	100%	
Electron temperature	100 MeV	100 MeV	
Secondary gammas			isotropic
Electron energy conversion	50%	50%	
Temperature	100 MeV	100 MeV	
Secondary ions	1000 nC	1000 nC	30^0 cone
Electron energy conversion	30%	30%	
Temperature	100 MeV	100 MeV	

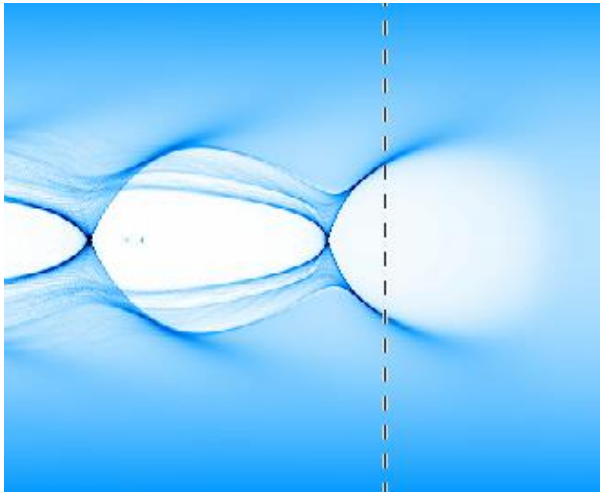
*

- The routine and maximum operational regimes are discriminated here by the assumed repetition rate only. There is no difference in physical nature of the radiation exposure for these two cases. The maximum radiation exposure will be proportionally 12 times higher to compare with routine.
- "Routine" regime is the typical mode of operation for user experiments. It can be an administratively imposed limit on the laser repetition rate if the radiation shield is impractically thick otherwise.


CPA
Compr.
Laser / e-beam
interaction
Femto-sec
Compressor
Regen
6-meter long
final amplifier
CPA
Stretch.
OPA
Ion
acceleration
9-11 μm
100 TW
100 fs
a_0=10
0.2 Hz
available in 2018

@ $n_p \ll n_{cr}$



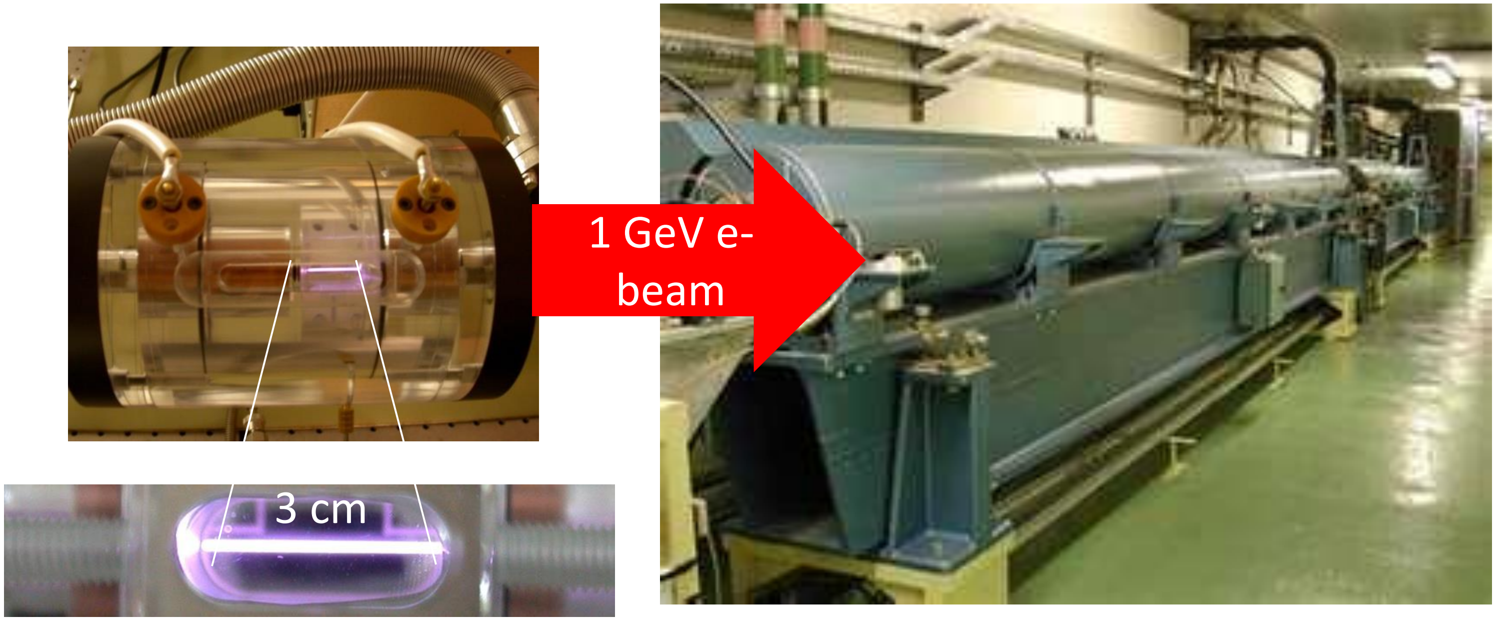


The magnitude of the accelerating field can reach

$E_0[\mathrm{V/m}] = 100(n_0[\mathrm{cm}^{-3}])^{1/2}$.

For $n_0 = 10^{16}\ \mathrm{cm}^{-3}$, $E_0 = 10$ GeV/m

(~300x beyond conventional RF technology)



100 TW CO_2 laser under construction
will enable 3 GeV electron beams of 5 nC charge produced in 0.5 m of plasma.

Experiment is in early planning stage

SUMMARY

We ask RSC to consider occupational hazards and required radiation protection for four areas where a 100 TW CO_2 laser to be built at ATF within next 2 years may produce ionizing radiation:

1. X-ray tubes inside a CO2 final amplifier will produce 3 Roentgen dose per shot localized inside a high-pressure amplifier vessel with 22-mm stainless steel skin. Laser operators can be present next to the laser during operation.
2. A mild laser focus inside a nonlinear compressor (metal vacuum vessel) will produce 1 MeV electrons and secondary radiation. Laser operator can be present next to the vessel during operation.
3. A strong laser focus in high-density gas or solid material capable to produce 100 MeV electrons and protons of the same energy. This is process is localized within a metal vacuum chamber positioned in radiation-shielded and interlocked area (Laser Experimental Hall).
4. A strong laser focus in a low-density gas to produce and accelerate electrons up to 3 GeV energy. This is process is localized within a metal vacuum chamber positioned in radiation-shielded and interlocked area. This could be in Laser Experimental Hall or Experimental Hall #1 with a 110 MeV linac beamline.